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TIME SAFETY MARGIN: THEORY AND PRACTICE

WILLIAM R. GRAY, III
Chief Test Pilot
USAF Test Pilot School

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TECHNICAL INFORMATION HANDBOOK

412TH TEST WING
EDWARDS AIR FORCE BASE, CALIFORNIA
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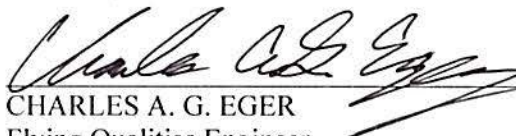
Prepared by:

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WILLIAM R. GRAY, III
Chief Test Pilot
USAF Test Pilot School

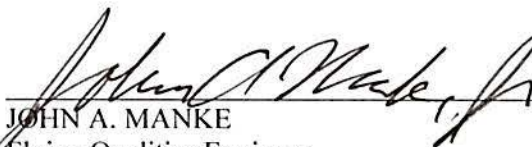This report has been reviewed and is approved for publication: 21 September 2016

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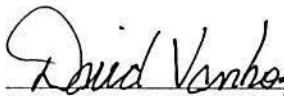Flying Qualities Engineer
773 TS/ENFB

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CHARLES A. G. EGER
Flying Qualities Engineer
773 TS/ENFA

_____

ALAN LARSON
Flying Qualities Engineer
773 TS/ENFA

_____

JOHN A. MANKE
Flying Qualities Engineer
773 TS/ENFA

_____

DAVID L. VANHOY
Technical Director
USAF Test Pilot School

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DAVID G. WHEATON
Technical Director
412 Test Wing

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14. ABSTRACT
Time Safety Margin (TSM) was developed in 2009 to provide risk reduction and aid in risk assessment for flight test maneuvers that include dives. TSM has become the standard method for flight test dive planning in the USAF. This handbook includes a short history of flight test dive planning and TSM, an explanation of the primary factors for dive recoveries, and an in-depth definition of TSM and its application in a regulatory framework. TSM is expanded to account for delayed recovery initiation. Following an introduction to the application of TSM, numerous TSM examples are provided. Several appendices are included to aid TSM planning, including charts for TSM estimation.

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PREFACE

Time Safety Margin (TSM) was originally developed following the catastrophic loss of Mr. David "Cools" Cooley during an unsuccessful high Mach, high altitude dive recovery following an F-22A test point. It was founded on the work of earlier test teams, especially Available Reaction Time (ART), a metric created by the F-16 Automatic Ground Collision Avoidance System test team. Special thanks go to Kevin Prosser of Calspan Corporation for his explanations of ART; Bill Kuhlemeier and Jim Brown of the F-22 Combined Test Force for their application of pilot reaction time to F-22 dive recovery planning in wings-level dives; Chris Childress and Aaron Reed of the 412th Operations Group for their insightful help with turning TSM into a regulation; and the 2009 Air Force Flight Test Center, Test Wing, and Operations Group leadership for their careful consideration and feedback. Much of the beginning of this handbook is based on a paper written with Jim Brown for the Society of Experimental Test Pilots in 2009 entitled *Time Safety Margin: A Generalized Method for Dive Safety Planning*.

In the intervening years, TSM has proven a valuable tool for dive safety planning and much has been learned about its practical application. This handbook has been prepared to provide guidance on the use and limitations of TSM. It also addresses a known shortcoming of the original TSM method; handling dives—such as a split-s maneuver—where an unexpected delay at the recovery initiation conditions can result in a much lower TSM than expected.

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INTRODUCTION

Diving maneuvers are common throughout flight test. Obvious cases include weapons deliveries or maneuvers designed to achieve conditions at high negative specific excess power (P_s)[1], but there are less obvious cases, including testing at unusual—even climbing—attitudes that will result in a dive following the completion of the test point. The wide variety of maneuvers, aircraft, pilot skill, and environments that may require or result in hazardous dives have historically driven the dive planning problem to be treated as a unique issue for each airframe or event. In the absence of proven guidance, test teams relied for many years on a mix of subjective engineering judgment (intuition) and objective planning to find the right balance of risk and mission accomplishment.

In the spring of 2009, the Air Force Flight Test Center (AFFTC)[2] at Edwards AFB experienced the very tragedy that all flight test professionals seek most to avoid; the loss of a colleague in the accomplishment of a test point. As the many necessary official investigative processes were underway, Dave "Cools" Cooley's friends and coworkers—including the author of this handbook—embarked on a course of intense introspection. They asked "What did we miss?" and sought to honor their friend by acting to prevent anything like it from happening again. In the difficult first few weeks following the loss, it became apparent that the astonishing performance characteristics of modern fighters had exceeded the intuitive understanding of some of the most experienced flight testers on the planet. The crash, proximately caused by insufficient altitude during a supersonic dive recovery, showed that the expectations of dive recovery requirements were limited by intuitions developed over decades of flying and testing earlier-generation fighter aircraft (reference 1).

Figure 1 F-22 Impact Crater

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[1] All abbreviations, acronyms, and symbols are defined in appendix D.

[2] In 2012, the AFFTC and several other United States Air Force Material Command (AFMC) test centers were combined to become the Air Force Test Center (AFTC). All references to the AFFTC refer to the earlier organization.

The AFFTC leadership quickly began the process of procedurally correcting this deficiency by instituting conservative dive planning requirements based upon operational techniques. These restrictions were quickly found to be overly conservative. While ensuring sufficient dive recovery altitude and "knock-it-off" procedures, they unnecessarily impacted many routine maneuvers and test techniques. With test teams providing this feedback and with the results of the F-22 Combined Test Force (CTF) mishap analysis and safety planning revision efforts clearly indicating the potential for a more nuanced approach, AFFTC leadership created the Dive Safety Working Group to bring a wide range of backgrounds and experience to the problem. Time safety margin (TSM) was the result of this effort. Time Safety Margin is most simply described as the time an aircraft conducting a maneuver that includes a dive may remain on its worst-case vector until the planned recovery will no longer be sufficient to prevent impact with the ground. By linking test point planning, training, buildup, and review requirements to the maneuver TSM, a rational and universally applicable approach to dive safety planning was instituted for USAF flight test planning.

As with flight test, the real testing isn't complete until the "user" has been exercising the system for a while. Routine application of TSM to test planning has shown that the method does not adequately capture the risk involved in maneuvers where the TSM is decreasing rapidly prior to the recovery. This isn't a problem so long as the TSM is not decreasing by more than one second for every second that the maneuver is continued, but if the TSM is decreasing by more than one second for every second then the actual risk of the maneuver may be much higher than the TSM indicates. Delayed Time Safety Margin (DTSM)—defined in this handbook—may be used to capture this effect in the TSM calculation.

TRADITIONAL DIVE PLANNING METHODS

Most pilots experience flying within the context of their current aircraft and focus exclusively on the procedures and techniques specific to that aircraft and environment. The wide variety of aircraft flying qualities and performance characteristics—and pilots—could create a bewildering variety of techniques, but pilots are not interested in being bewildered; they want the simplest set of rules that work. Thus, simple rules-of-thumb are evolved in one community, transmitted to others, and perhaps eventually written as regulations. If these rules become regulations their origin and environment are rapidly forgotten, making it more likely for them to be adopted by other communities for situations to which they may be less suited. Regardless, once these rules are adapted and published, they live unquestioned in virtual perpetuity.

The necessity of planning for dive recovery has created a variety of techniques and requirements. The origin of these methods can be surmised by examining where and when they work. We will examine some of these rules, speculate on their origin, and see where they can become traps.

LINEAR RULES

Linear rules are simple methods for relating an altitude above ground level (AGL) with a dive angle. The exceptionally simple "50% Rule" is common in communities that have relatively low g[3] limits. If you are diving (in degrees) at more than half your altitude above the ground (in hundreds of feet) you are too steep for comfort. (The 50% rule has also been called the "AGL/200 Rule" or "Rule of 200." For a short time following the 2009 F-22 mishap, the AFFTC used the "Rule of 200" to set the maximum allowable dive angle for flight test dives.) Figure 2 depicts typical guidance for this rule as published in the Chief of Naval Air Training (CNATRA) manual *Low Altitude Awareness Training* (reference 2). In contrast, the "AGL/100 rule" is more suitable for fighter-type aircraft. According this rule the maximum dive angle is simply the AGL altitude in feet divided by 100, so 4,500 ft AGL would correspond to a maximum dive angle of 45 degrees.

> **The 50% rule** is a simple set of do-not-exceed dive angle numbers corresponding with specific AGL altitudes that ensure a safe expeditious descent from 5000 ft AGL to a point where the dive recovery rules apply. For example a pilot at 4000 ft AGL would use a 20° FPA until reaching 3000 ft AGL then decrease his FPA to 15° until 2000 ft AGL and so on.
>
> | Altitude (AGL) | Dive Angle |
> | --- | --- |
> | 5000' | 25° |
> | 4000' | 20° |
> | 3000' | 15° |
> | 2000' | 10° |
> | 1000' | 5° |

Figure 2 The 50% Rule reproduced from CNATRA *Low Altitude Awareness Training*

Linear rules have the advantage of being simple and easy to use "on the fly." But dive recovery altitudes do not vary linearly with dive angle, and the specific relationship—be it the "Rule of 200," the "AGL/100 Rule," or some other rule—comes with unspoken and too-often unrecognized assumptions about aircraft speed and performance capability. For instance, figure 3 depicts the 5 g-recovery flight path for three aircraft at different airspeeds, each starting at the minimum altitude for a vertical dive using the AGL/100 rule. It is

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[3] Pilots typically refer to cockpit normal acceleration (N_z), as "G" or "g" reflecting the convention of expressing the N_z in units of local gravitational acceleration. "g" will be used as shorthand for "g N_z" in this handbook.

clear that this rule came from the classic fighter community because the 0.9 Mach number (MN) recovery is completed with altitude to spare. At very low and very high speed, the rule fails; a small aerobatic aircraft at 180 KCAS completes the recovery with a grossly over-conservative margin while an aircraft recovering at 1.6 MN hits the ground while still in a 63-degree descent!
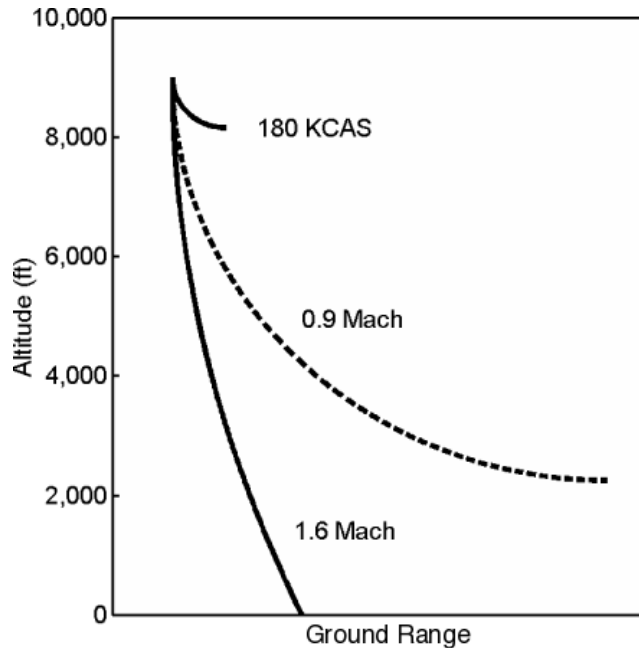
Figure 3 Constant 5-g Recovery Paths for Three
Different Airspeeds

MINIMUM SAFE ALTITUDES

Minimum safe altitudes (MSAs) are the most common safety rules for reducing the risk of ground impact. A few examples of MSAs are minimum altitudes for certified airshow demonstration pilots, minimum recovery altitudes for bomb ranges, minimum altitudes for aerobatic flight, and "the floor" for practice air-to-air combat. The pilot is relied upon to use planning and airmanship to assure that these limits aren't exceeded.

Unfortunately, MSAs poorly address the likelihood of the pilot making a fatal error. For instance, if the minimum altitude for aerobatics is 5,000 feet AGL a pilot can make a pretty significant error and survive. This is not the case with an MSA for a low-angle strafe run—typically 75 feet AGL—where a too-steep approach or slight delay in initiating recovery can result in disaster. Minimum safe altitudes typically provide a limit that is used to develop procedures and training to ensure that the MSA is not violated, but pilots may not be aware of the actual margin for error that any given MSA provides.

PRE-TSM FLIGHT-TEST DIVE PLANNING METHODS

Flight test dive planning at the AFFTC prior to 2010 was the responsibility of the test team. Each test team chose or developed a methodology that suited their needs. Their plan was independently reviewed and approved prior to initiating test flights. Most of the time, informal methods were used that were almost entirely based on the test pilots' experience and the expectations of the independent reviewers and approval authorities. One test team made an important conceptual leap in the mid-1990's while planning

for automatic ground collision avoidance testing (GCAS), but their ground-breaking methodologies were not applied outside of their test; they viewed their technique merely as a risk-assessment method for GCAS tests.

Informal Methods:

Most flight test dive planning history—at least the result of that history—can be summarized quite simply. First, test teams examined their flight test maneuvers and determined which ones had a significantly increased risk of ground impact. This was typically accomplished using the advice (intuition) of the test pilots regarding which maneuvers may cause problems, ideally taking into account other factors such as pilot workload and the system under test. Then, for those maneuvers perceived to carry significant risk, dive recovery predictions and/or simulator rehearsals were utilized to adjust test point conditions and determine the minimizing procedures necessary to control risk. The problem with this methodology was not the creation of minimizing procedures, it was the threshold for requiring additional planning. At the AFFTC, there were several "rules of thumb" that drove this threshold. First, basic operational rules for fighter aircraft were readily available and routinely used. Second, and for all aircraft, 5,000 feet AGL was seen as the altitude below which dive recovery became more critical. The implication was that as long as the recovery would be completed above 5,000 ft AGL, the maneuver was low risk.

These informal methods resulted in an almost schizophrenic approach to dive recovery; they had a history of success but little rational basis. For large or low-g aircraft, descents in excess of about 10 degrees below 5,000 feet AGL often drove additional minimizing procedures—such as simulator practice and a buildup approach to the desired recovery altitude—in spite of only needing several hundred feet to recover. For fighter aircraft, the threshold for concern had less to do with altitude (5,000 feet AGL was clearly too low for very steep high-speed dives) and more to do with rules-of-thumb and pilot experience. Reliance on rules-of-thumb and intuition had resulted in a situation where the F-22 CTF was beginning 1.6 MN, 9 g "split-s" flight test maneuvers at about 25,000 feet AGL[4] (under-conservative) while the C-17 CTF was required to build-up to 20-degree dives at 3,000 feet AGL (over-conservative).

Available Reaction Time:

"Available Reaction Time" (ART) was a planning methodology developed for an F-16 ground collision avoidance test in the mid-1990's. A paper on the method entitled *The A.R.T. of Ground Collision Avoidance Testing* (reference 3), was presented at the 1999 Society of Experimental Test Pilots Annual Symposium by LtCol Bob Wilson and Mike Seelos.

The algorithm for the F-16 GCAS was designed to prevent the aircraft from going beneath a pre-selected minimum altitude above the ground. A buildup process was conducted by artificially raising the surface elevation database—and consequently the minimum recovery altitude—so that the automatic recovery could be evaluated without unnecessarily endangering the pilot and aircraft. Nevertheless, there were clearly diving maneuvers where the expected minimum altitude gave the pilot little reaction time to correct a GCAS deficiency. The hazard of these maneuvers increased as the altitude buffer was decreased. The GCAS team researched human reaction time and used this data to create the risk ranges depicted in figure 4.[5] Figure 5 depicts the graphics from the paper showing how an altitude buffer was used to plan the profile and ART

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[4] It must be noted that while the maneuver was intended to be flown without exceeding about 45-degree descent angle, nobody was particularly concerned that pulling through in a complete 9-g "split-s" maneuver represented a significant hazard.

[5] Alert readers will have noticed the similarities between the ART times and TSM times. The NASA F-16 Auto-GCAS program, from which some AFFTC TSM boundaries were obtained, built upon the mid-1990's GCAS program and used the same risk assessment technique with a few minor alterations.

was calculated to assess the risk.

The ART methodology was an extremely successful risk-assessment technique, but it was seen as only that. Several quotes from the paper drive this home:

> In conclusion, we believe A.R.T. is an excellent normalizing factor that can be used for any given ground collision avoidance system test point regardless of the system or aircraft under test.
>
> ...we conclude this paper with the assertion that A.R.T. is *merely* a tool available for use in assessing test point risk. [italics added]

The authors envisioned ART as a risk assessment method for ground collision avoidance system testing when the methodology, in hindsight, had much broader potential as a planning method for most wings-level diving maneuvers.

The ART and TSM methods were independently founded on the core principle that the critical safety parameter for dive recoveries is not altitude, airspeed, dive angle, or any other indication provided in the cockpit; it is the time available for the test team to react to unplanned deviations that could result in impact with the ground.

A.R.T. (seconds)	RISK
greater than 2, less than or equal to 3	HIGH
greater than 3, less than or equal to 4	MEDIUM
greater than 4	LOW

Figure 4 ART Risk Assessment Requirements (reference 3)

Figure 7 GCAS Profiles Summary

Figure 6 Available Reaction Time (A.R.T.)
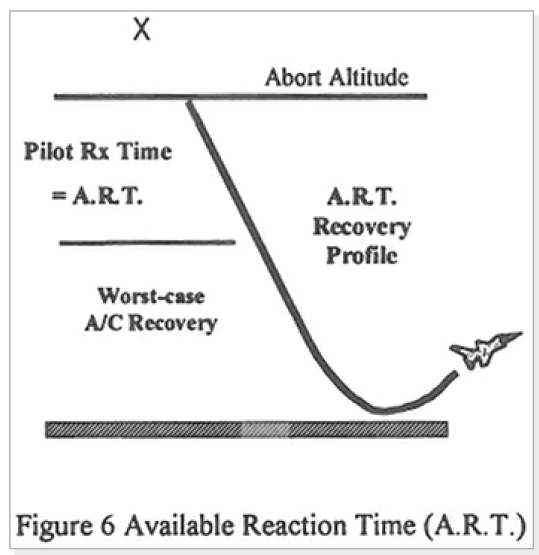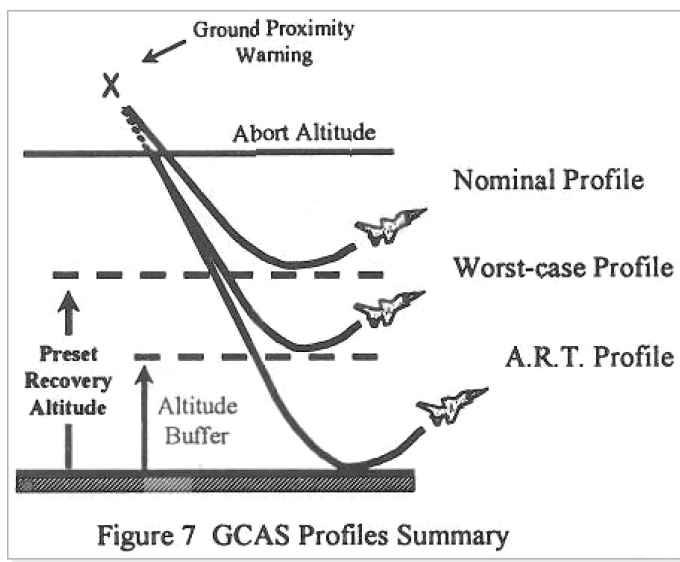
Figure 5 ART Figures Depicting Altitude Buffer and Pilot Reaction Time (reference 3)

THE ROLE OF INTUITION IN PLANNING

"Intuition" is defined as "instinctive knowing (without the use of rational processes)" by Princeton University's *WordNet* lexical database (reference 4). Intuition is a key part of airmanship because pilots are so often required to make decisions without the time or information for a judicious process. In spite of the confidence most people place on their intuition, intuition is best treated with skepticism. For instance, human beings are relatively adept at projecting linear conditions to predict spatial positioning so pilots, being human, tend to subconsciously linearize most conditions. So, while the "on the wire" dive problem is linear and easily understood, highly non-linear entry and recovery conditions can quickly render the pilot's intuition inadequate. While valuable when properly developed and applied in the correct context, intuition can lead to confident and comfortable dependence on blind luck. When the F-22 CTF and the AFFTC examined the circumstances of the 2009 F-22 mishap, the most common reaction was surprise: How was it not obvious that about 13,000 feet was required for a 9-g recovery from a 1.6 MN vertical dive? The intuition borne of years of flying and testing fighter aircraft was clearly inadequate. A rigorous process was needed.

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DIVE PLANNING FACTORS

There are many factors to account for when determining the altitude lost during a dive recovery. It does not help that as the margin for recovery becomes smaller each factor gains importance, both alone and in combination with the others. Factors that are inconsequential at higher altitudes may make a life-or-death difference closer to the ground. Some of the more important planning factors are altitude, airspeed, dive angle, bank angle, roll rate, recovery N_z, N_z onset rate, aircraft performance, unique aircraft characteristics,[6] and pilot skill.

NORMAL ACCELERATION (N_Z)

Recovery N_z (traditionally measured in units of gravitational acceleration, "g"), is correctly understood as a very important dive recovery component but it is not immediately apparent that as the N_z increases the incremental effect of the added N_z decreases. Figure 6 depicts constant N_z recoveries at 0.8 MN starting from a vertical dive at the same altitude. Note that the relationship between N_z and altitude loss is not linear. As the N_z increases, each additional g added to N_z increases the N_z by a smaller percentage of the total N_z. For instance, going from 2 g to 3 g increases the N_z by 50 percent but going from 8 g to 9 g only increases the N_z by 12.5 percent. Note also that the curves are not circular arcs; the radius increases as the dive angle decreases. As N_z decreases gravity takes a higher toll at shallow dive angles. In a shallow dive, half of a 2-g pull is dedicated to opposing gravity and has no effect on the radius of the flight path, while in the same shallow dive angle at 8 g only 12.5 percent of the pull is used to counter gravity. Neither of these "lessons" is the least bit complex or surprising yet most pilots find it hard to believe that for these constant Mach and N_z vertical dive recoveries, the difference in altitude loss between 2 g and 3 g is within 5 percent of the difference in altitude loss between 3 g and 9 g.[7]
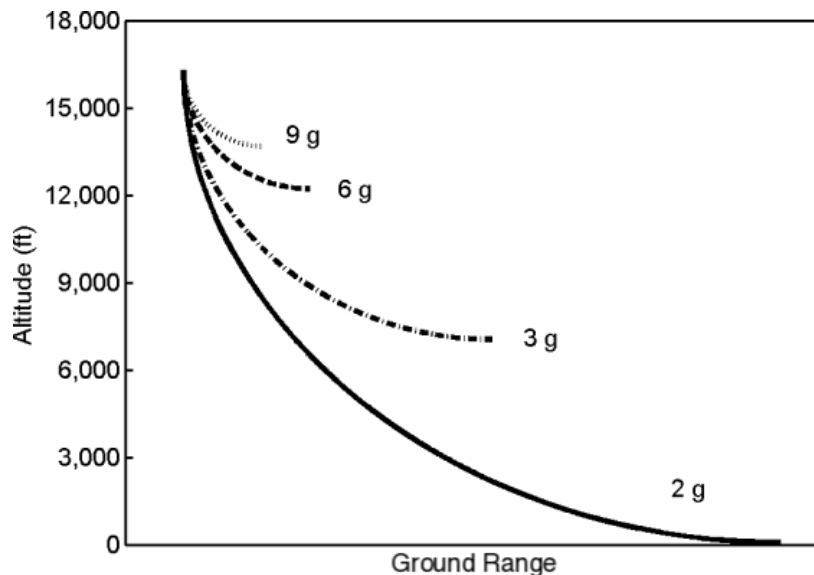
Figure 6 The Effect of N_z on Dive Recovery

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[6] Characteristics such as high-Mach RPM lockup, delayed afterburner cancellation, N_z limiters, and maneuver load alleviation (including automatic speedbrake retraction) can significantly limit a high-speed/Mach recovery without being evident to the pilot during the maneuver.

[7] Returning to figure 3, if a 9-g pull is used instead of the 5-g pull depicted, it will still be much less than required for a successful recovery at 1.6 MN; impact will occur in a 37-degree descent.

TRUE AIRSPEED AND MACH NUMBER

True airspeed and Mach number are closely related. Mach number (the ratio of the aircraft true airspeed to the speed of sound) and the true airspeed tend to be fairly proportional thanks to the slow change of the speed of sound with altitude. An aircraft traveling at Mach 1 at 50,000 ft MSL is only moving about 13 percent slower than an aircraft at the speed of sound at sea level. Most dive recoveries take much less than 50,000 feet so we can assume that the effect of Mach number and true airspeed are the same.

At a constant acceleration, the turn radius is proportional to the true airspeed. In the simplest case, the instantaneous wings-level dive turn radius, r, is related to N_z and dive angle (γ) by the following equation, where g is the local acceleration due to gravity:

$$r = \frac{V_t^2}{N_z - g\cos\gamma}$$

N_z is predominantly the ratio between the lift and weight of the aircraft multiplied by g.

$$N_z = g\frac{L}{W} = g\frac{\frac{1}{2}\rho V_t^2\, C_L S}{W}$$

By substituting the equation for N_z into the turn radius equation, we find:

$$r = \frac{V_t^2}{g\left(\frac{\frac{1}{2}\rho V_t^2\, C_L S}{W} - \cos\gamma\right)}$$

$$\text{where cockpit } N_z = \frac{\frac{1}{2}\rho V_t^2\, C_L S}{W} \text{ in units of g.}$$

The effect of V_t on the instantaneous turn radius is highly dependent on the dive angle and the cockpit N_z. If the dive angle is very steep, $\cos\gamma$ is approximately nil and the V_t^2 terms cancel out. This means that at very steep dive angles the turn radius does not change with airspeed so long as the aircraft gross weight (W) and coefficient of lift (C_L, approximately constant for a given angle-of-attack (AOA) in subsonic flight) are the same. If the dive angle is very shallow, $\cos\gamma$ is approximately equal to 1. If the N_z is close to 1 g, the turn radius grows with the true airspeed but as the N_z increases, the turn radius becomes less dependent on true airspeed.

To a pilot faced with a dive recovery, the airspeed is typically dictated by the situation so all the pilot can do is increase the N_z as high as necessary (or possible) to affect a recovery. There must also be enough N_z available for recovery. As the dive shallows, the radius of the dive increases. In a vertical dive all of the N_z is turning the aircraft but, as the aircraft approaches level flight, only $N_z - 1$g is turning the aircraft.

CALIBRATED AIRSPEED AND DYNAMIC PRESSURE

An aircraft produces lift by acting on the air roughly in accordance with the two-dimensional lift equation,

$$L = \bar{q}C_L S \text{ where the dynamic pressure } \bar{q} = \frac{1}{2}\rho V_t^2$$

Equivalent airspeed (EAS) is the airspeed defined by constant dynamic pressure, $\bar{q}$. At a given equivalent airspeed, the dynamic pressure is the same regardless of altitude.

Equivalent airspeed and calibrated airspeed (CAS) are very close for dive recovery considerations. (Compressibility has little effect on CAS at low altitude). For most aircraft, the stall speed is defined as the first local maximum of the coefficient of lift, C_L as the AOA is increasing. At subsonic speeds, this maximum C_L at stall represents the maximum N_z available for recovery and this maximum lift point is achieved for a given N_z at the same subsonic CAS regardless of altitude. This marks the low end of the dive recovery airspeed; if the CAS is not above the stall speed, the recovery cannot be completed in a conventional aircraft.

On the high end of CAS, the "corner speed" creates another challenge. The corner speed is the lowest speed at which the aircraft can achieve the structural limit N_z. Above this speed, the N_z may be increased but only at the cost of over-g and the risk of structural damage or failure. If the pilot respects the N_z limit, the turn radius increases rapidly as airspeed increases above the corner speed.

Dive recoveries are best accomplished in a range of airspeed between too slow to recover (near or below the stall CAS) and so fast that recovery without risk of structural damage (faster than the corner CAS) cannot be accomplished without significantly increasing altitude loss. Pilots are typically trained to use high power settings for slow nose-low recoveries and low power settings (plus drag devices, if required) for high speed nose-low recoveries that might exceed the corner speed.

INITIAL AIRCRAFT ATTITUDE AND RECOVERY TECHNIQUE

Aircraft attitude and N_z at the initiation of the recovery maneuver bring in several layers of complexity. At high bank angles, unloading to roll, rolling to an upright attitude, and pulling to the recovery N_z add to the altitude loss. Figure 7 depicts three 7-g dive recoveries from a 45-degree descent at 0.9 MN. The first case, resulting in minimum altitude loss, has the aircraft just continuing a 7-g pull. The second case has the aircraft starting at about 0.7 g (maintaining a constant flight path angle) and pulling to 7 g at 3 g/sec, resulting in about a 50 percent increase in altitude loss. The final case has the aircraft inverted at 7 g, much like what might be required in a "Split-S" flight test maneuver. After unloading to 1 g in 2 seconds, rolling upright at 90 degrees per second, and pulling 3 g/sec to attain 7 g, the total altitude loss exceeds *five times* the altitude loss of the simple 7-g pull. The altitude loss is so great that the "AGL/100 rule" is rendered unsafe. For steep dive angles, the altitude lost to unloading and rolling to a wings-level upright attitude can be so great that after pulling to an inverted dive of approximately 70 degrees at high g, continuing to pull through the vertical is usually the best maneuver to minimize altitude loss.

AIRCRAFT-SPECIFIC CONSIDERATIONS

Every aircraft brings its own limitations to a dive recovery. Some limitations are immediately obvious, such as flight-manual mandated N_z limits and the stall angle-of-attack. Pilots are intimately aware of these limitations and should be trained to apply them to their dive recovery problems. Aircraft outfitted with stability and control augmentation systems often have additional characteristics that may provide an unexpected surprise during a high-stakes dive recovery.

Asymmetric Load Limitations:

In earlier-era aircraft, pilot skill was the sole method to ensure that the asymmetric load limit was not exceeded. Given the complexity of aerobatic flight and high-load combat maneuvering, pilots often developed the habit of unloading to trim (usually 1 g N_z) prior to making any significant rolling maneuver.
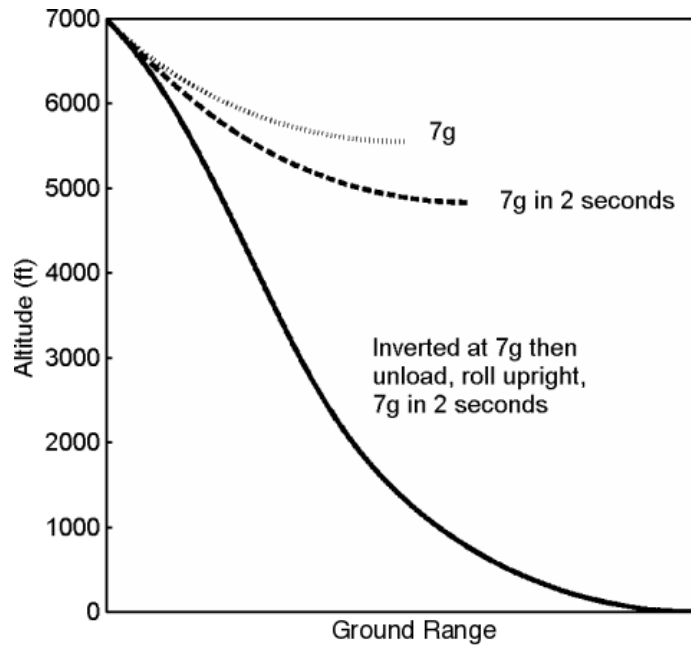
Figure 7 The Effect of Simple Maneuvers on a 0.9 MN
Dive Recovery

During an upright dive recovery unloading to roll will increase the altitude loss, but in an inverted dive unloading to roll will typically decrease the altitude loss. It is likely that a pilot with these habit patterns will inadvertently increase altitude loss during an upright dive recovery. Many modern aircraft incorporate flight control systems that allow "carefree maneuvering." With these aircraft, pilots need not be concerned about asymmetric over-stress and unloading to roll is unnecessary. Perhaps these pilots are more likely to increase altitude loss in a inverted dive by not unloading prior to the roll.

Flight Control System Limiters:

The most obvious flight control system (FLCS) limiters include N_z, roll rate, and angle-of-attack limits imposed to allow the pilot to "max perform" the aircraft with minimum risk of over-stress, departure, or stall. These systems are rarely as simple as they first appear. For instance, it is not unusual for additional roll rate and N_z limits to be imposed at higher angles-of-attack. Dive recoveries must be planned within these additional limits to prevent excess altitude loss that can occur from achieving less-than-expected roll rates or N_z.

Load Alleviation Systems:

Load alleviation systems reduce the likelihood of over-stress and increase the expected lifetime of an airframe by monitoring critical points for structural loads and limiting the aircraft performance as necessary to prevent exceeding a preset limit. These systems have produced unexpected reductions in the anticipated roll rate and N_z, an obviously hazardous result during a low-margin dive recovery.

Engine Stability Augmentation:

Engines outfitted with stability and control augmentation systems can produce an extraordinary amount of thrust or power with excellent reliability and "care-free" operation. These characteristics do not come without a price, though, as pilots occasionally discover when they find that a request for IDLE power is

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answered with full MILITARY power as the engine does what it must to continue stall-free operation. An engine can produce more—or less—thrust than expected as it runs its program to maintain stability across a large aircraft envelope. An unexpectedly high power setting can significantly increase the altitude lost in a dive recovery at maximum N_z.

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TIME SAFETY MARGIN

THE DEVELOPMENT OF TIME SAFETY MARGIN

The tragic loss of Mr. Cooley and his F-22 at the AFFTC in 2009 showed that the dive recovery planning methods used with confidence and apparent success for years could not be fully trusted. As conservative planning requirements were put in place across the AFFTC, the F-22 CTF was tasked with developing a new approach toward accomplishing their $-P_s$ testing. This approach would have to account for all elements of the dive planning problem. The CTF was also directed to ensure that, as a minimum, all diving test points had defined planned and abort dive angles, planned and abort recovery altitudes, and standard procedures to be used when executing either the planned dive recovery or abort dive recovery. While developing this new approach, CTF members developed "Time to Impact (TTI)" as a means of assessing risk. Their approach— formalized in the test and safety planning change required to continue the mishap test points—was then independently evaluated by an AFFTC Safety Review Board (SRB). The SRB recommended that the CTF subtract from TTI the time beyond which recovery was not possible. The F-22 CTF incorporated this recommendation and calculated a "Time to Unrecoverable (TTU)" for each maneuver. In order to capture the most conservative TTU, the worst-case conditions on the test point were used as the starting conditions (highest speed, lowest altitude, steepest dive, etc.).

With a solution in place for the F-22, the AFFTC turned to dive planning in general. the AFFTC Dive Safety Working Group was formed to develop a broadly-applicable method for dive safety planning. As it was about to assemble for the first time, email traffic between members grew as they shared their organizations' methods and thoughts. All of these methods had a common simplification; they focused on the 2-dimensional problem of diving wings-level flight. The working group needed to find a method that was comprehensive enough to be suitable for a wide variety of aircraft and missions, ranging from USAF Test Pilot School students flying single-look qualitative evaluation sorties in small aerobatic aircraft, to bomber aircraft testing emergency descents, to transport aircraft conducting ground proximity warning tests, and to fighters at very high Mach numbers and steep dives. A method was needed that allowed for planning for complex 3-dimensional maneuvers such as wind-up turns and slice-backs.

In the hope of seeing the problem more clearly, the author wrote a software tool that allowed examination of the problem with all critical aircraft-independent factors taken into account.[8] Running multiple examples confirmed that the problem was not sufficiently accounted-for by any of the rules-of-thumb or aircraft-specific methods. Nevertheless, several things became clear. First, every dive recovery had a point that best encapsulated the severity of the dive; the lowest AGL altitude of the steepest dive angle of the maneuver—the "worst-case vector." Second, every unsuccessful dive recovery had a point where impact with the ground was inevitable, obviating the need to consider risk reduction measures after that point and clarifying the necessity of never getting there. Finally, as the maneuver was started at lower and lower altitudes, one thing varied in a very straightforward and essentially linear way—the time that the aircraft could remain on the worst-case vector until the planned recovery would become insufficient to complete a recovery. The author named that time "Time Safety Margin".

With TSM as a common metric for all dive recoveries, it was immediately apparent that general categories divided by specific TSM values could be used to characterize the risk of a maneuver and, consequently, the type and amount of mitigation required to ensure safe recovery. But where to draw these boundaries? Boundaries at 4 seconds (medium risk), 2.5 seconds (high risk), and 1.5 seconds (exceptionally

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[8] A more user-friendly graphical user interface version of this tool, the "Time Safety Margin Awareness Tool" written for MATLAB and documented in appendix C, is freely available. This tool was used for the examples in this handbook.

high risk) were taken from the ART risk assessment method that had grown with the NASA/USAF automatic ground collision avoidance flight tests. These boundaries were based on pilot reaction time—a valid way of thinking about TSM: "How much time can the recovery be delayed at the worst conditions?" Although a ten second boundary for "routine" recoveries was initially considered, examination of several real-world training programs revealed that 8 seconds was a more reasonable value.

The author proposed TSM to the Dive Safety Working Group and they quickly agreed to pursue it as the basis for a generalized risk mitigation methodology for diving maneuvers. The final definition and approach—as incorporated into AFFTC instructions in 2009—nicely encapsulates the important issues in the computation and use of TSM and is presented later in this handbook.[9]

Time Safety Margin is a time-based parameter calculated for a given maneuver, it is not the regulatory framework built around the parameter; the regulatory framework should be developed to meet the needs of the organization using TSM.

THE DEFINITION OF TIME SAFETY MARGIN

Time Safety Margin is designed to provide a measurement of safety margin to an entire test maneuver, beginning at the start of the test procedure and ending at the completion of the dive recovery. The term "procedure" refers to the intended test procedure and the term "recovery" refers to the recovery to level flight following the completion of the procedure. Figure 8 depicts these terms in a simple constant-angle dive entered using a push-over from level flight.

- "Procedure start"—The starting point of the maneuver. Although it is reasonable to assume that this point coincides with the "cleared to maneuver" call, room must be left for ambiguity; it is possible for the setup for the test procedure to include a more-hazardous dive than the procedure itself. In this case, the procedure should include the setup.

- "Procedure"—The flight path from the start of the procedure to the start of the recovery.

- "Planned recovery start"—The point at which the procedure is completed and recovery is initiated including planned test team and/or pilot reaction time. This may follow the successful completion of the test point/procedure, the decision to recover in lieu of pursuing a failing attempt (typically called a "termination"), or the decision to recover as preset limits are exceeded (typically called an "abort").[10]

- "Recovery end"—The completion of the recovery on a vector that assures ground clearance; typically level flight.

- "Maneuver"—The entire planned event from the beginning of the procedure to the completion of the recovery.

The rest of the terms are needed to define TSM.

- "Worst-case vector"—The point during the maneuver where the aircraft is at the lowest altitude for the fastest descent rate. This point should be determined by assuming that the entire maneuver is executed using the least-conservative allowable conditions.

- "TSM path"—A straight-line flight path connecting the worst-case vector with the start of the continued maneuver. TSM is the time the aircraft spends on this flight path. Aircraft performance should

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[9] In the intervening years, the regulatory guidance has become slightly more generalized, somewhat more restrictive (TSM less than 1.5 seconds is not allowed), and elevated to the Major Command level.

[10] Late recognition of exceeding the abort parameters would result in an unplanned reduction in the TSM and would be cause for an immediate safety-of-flight recovery (typically signified with a "knock-it-off" call).

be considered to adjust the airspeed of the aircraft on the TSM path, but the path itself is entirely described by the direction the aircraft is moving at the worst-case vector.

- "Continued maneuver"—The worst-case planned maneuver is continued from the conditions of the worst-case vector except at the altitude and airspeed calculated for the end of the TSM path.
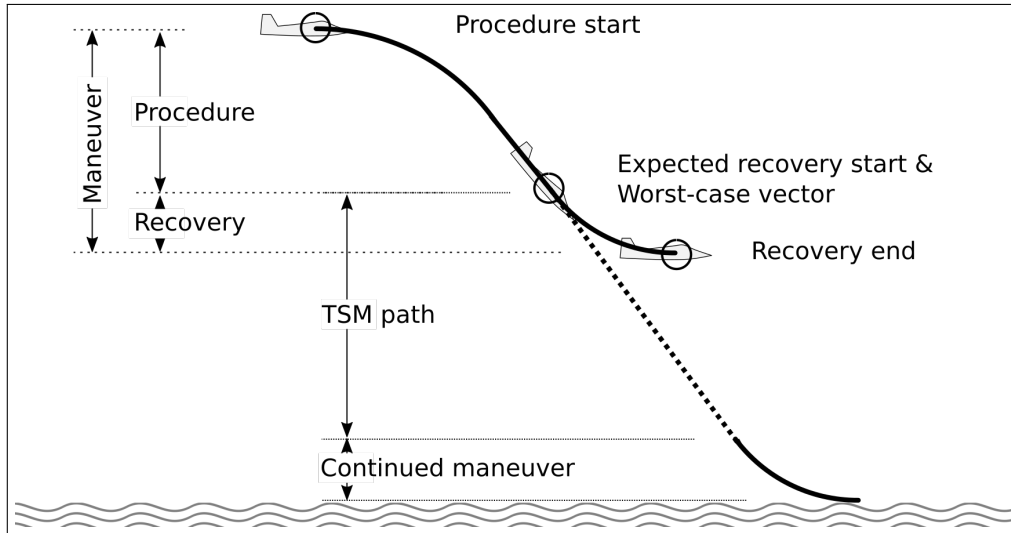
Figure 8 Basic Dive Recovery Terminology

The Simplest Definition of TSM:

Time Safety Margin is the time to directly travel from the worst-case vector to an unrecoverable condition. It is estimated by first defining a least-conservative combination of procedure and dive recovery, then by identifying the resulting worst-case vector in the resulting maneuver (which may be in either the procedure or the recovery), and finally by finding the longest amount of time that the aircraft can spend on the path described by the worst-case vector before continuing the maneuver would not result in ground impact.

THE ORIGINAL TSM REQUIREMENTS

After working through the many implications and practicalities of deploying TSM at the AFFTC, official guidance for TSM was published in a supplement to the Air Force Instruction (AFI) for flight test operations. The original guidance has been adjusted somewhat over the years, including eventual incorporation into the AFIs so that it became required practice for all USAF flight test operations. *Only the original requirements are presented here; it is the responsibility of USAF readers to comply with current requirements.*[11] This guidance, provided in the 2009 AFFTC Supplement 1 to AFI 11-2FT Volume 3, *Flight Test Operations Procedures* (reference 5) read in part:

> For all test points that require or result in a dive (gamma less than 0 degrees) and are not operationally published maneuvers..., test teams will use the procedures outlined in [figure 9] to minimize the risk of controlled flight into terrain (CFIT). Dive recovery planning and safety review board (SRB) requirements will be dependent upon the Time Safety Margin (TSM). TSM is defined as the time in seconds to directly travel from the worst case vector (i.e. worst case combination of parameters: dive angle, attitude, airspeed, and available N_z that includes both planned and maximum allowed deviation/tolerance) to an unrecoverable condition.

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[11] See appendix B for the draft requirements for AFI 11-2FTV3 as of July 2016.

With TSM as a single parameter applicable to all dive recoveries, requirements could be set according to TSM. These requirements, depicted in figure 9, were divided into five categories, increasing in assumed risk and planning requirements as the TSM decreases from 8 seconds, the minimum for "routine" dive recovery, to 0 seconds, where assumed risk and required planning reach their necessary maximum. The table and notes were created in coordination with members of the Dive Safety Working Group and AFFTC leadership. Although specific to the AFFTC at the time, the table contains some valuable considerations.

	Routine (TSM ≥ 8)	Focused (8 > TSM ≥ 4)	Aided (4 > TSM ≥ 2.5)	Redundantly Aided (2.5 > TSM ≥ 1.5)	Automatic (1.5 > TSM ≥ 0)
Minimum Planning Fidelity[1]	Flight Manual	M&S	Best available M&S	Best available M&S	Best available M&S
Recovery Procedure[1,2]	Routine[3]	Defined and Documented[4]	Defined and Documented[4]	Defined and Documented[4]	Automatic[4]
Minimum Training/Buildup[5]	Not Required	In-Flight Buildup	Sim Rehearsal[6] & In-Flight Buildup	Sim Rehearsal[6,7] & In-Flight Buildup	Sim Rehearsal[6,7] & In-Flight Buildup
Recovery Initiation[8]	Pilot	Pilot	Back-up for Pilot[9]	Two back-ups for Pilot[10]	Automatic
Presumed Risk Assessment	Low	Low	Medium	High	High[11]

Notes:
1. SRB will validate both the dive planning modeling and simulation (M&S) and the planned recovery procedure for all recoveries other than routine.
2. The recovery procedure will be planned not to exceed 80% of available aircraft limits at flight conditions and to minimize any combination of high-g, g dwell time, high-g onset, and rapid transition from negative to positive g.
3. Immediately initiate recovery after test point is complete.
4. Test team will document the planned test parameters, abort parameters and recovery
5. In-flight buildup maneuvers will be accomplished with a minimum computed TSM of 8 seconds. Test teams will validate predictions via buildup points before proceeding to test points."
6. Simulator rehearsal requirements will include practicing the complete recovery procedure. SRB simulator rehearsal requirements may be waived on a case by case basis by the test safety package approval authority.
7. Currency for the pilot flying the maneuver and critical test team members will be determined by SRB, but no longer than 6 days for TSMs less than 2.5 seconds.
8. All available onboard altitude awareness devices will be briefed and used.
9. The recovery initiation back-up may be provided by an on-board safety crewmember, a chase aircrew, or control room personnel.
10. At least one of the two recovery initiation back-ups must be external to the test aircraft.
11. Human action (i.e. "abort" calls, pilot input, etc.) may not be considered "risk mitigating."

Figure 9 AFFTC TSM Planning Matrix and Notes (reference 5)

TSM Time Range Requirements:

The time range requirements were created to provide initial guidance on how TSM should affect the level of planning, effort, and risk for a particular diving maneuver. The time ranges are necessarily stair-stepped, much like a risk-assessment matrix from systems safety methods, but the actual change in risk and required planning effort is more like a smooth curve. This curve approaches zero cost and risk at very high TSM and asymptotically approaches an unachievable maximum of cost and risk at 0 seconds of TSM. Thanks to

the additional cost created by higher risk assessments, metrics like these will drive test teams to design to a pre-determined minimum TSM. It is helpful to keep in mind that the actual safety risk between, say, 8.1 and 7.9 seconds of TSM is probably inconsequential.

Routine (TSM≥8 Seconds).

If the TSM is 8 seconds or more, the maneuver is considered "routine" in the sense that a routinely qualified pilot can be trusted to safely recover using routine planning and recovery procedures, and no further safety mitigation is required. Operationally representative maneuvers that typically have 8 seconds or more TSM include instrument descents and subsonic aerobatics with a 5,000-foot-AGL floor.

Focused (8>TSM≥4 Seconds).

"Focused" TSM, although still considered to present a low risk of ground impact, requires the pilot to have additional training and the test team to conduct additional planning. Inflight buildup is also required to verify predictions and provide the test team with the opportunity to practice. Operational maneuvers with this much TSM may include diving weapons deliveries, simulated flameout landings, and other maneuvers that require additional training and a specialized qualification.

Aided (4>TSM≥2.5 Seconds).

When the pilot's reaction time becomes a factor for safe recovery, it becomes necessary to provide assurance that a recovery command is given. In addition to a redundant recovery call, "Aided" TSM requires use of the "best available" modeling and simulation, and rehearsal in a suitable simulator. There are operational maneuvers that fall in this category but, as in the case of some weapons deliveries, they tend to be seen during particularly aggressive maneuvers. Maneuvers with TSM in this range are initially assessed as "medium risk," requiring additional review and oversight.[12]

Redundantly Aided (2.5>TSM≥1.5 Seconds).

When TSM is 2.5 seconds or less, any delay in recovery can be critical, so an additional back-up source for the "recover" decision is required. Operational maneuvers in this range are rare, but include low-angle strafe attacks. Airshow maneuvers tend to fall in this category as well. Both of these examples require an immense amount of training and practice, usually with a radio-capable ground observer and methodical buildup practice sessions. At the AFFTC, these test points are initially assessed as "high risk," requiring the most extensive review and oversight.

Automatic Recovery (1.5>TSM≥0 Seconds).

At some point the human pilot should not be trusted to safely recover without an extraordinary amount of training and its attendant cost, regardless of mitigating procedures and external support. There are airshow maneuvers and worst-case low-angle strafing attacks that fit within this TSM range, but the risks of accepting this almost insubstantial margin drive training costs and residual risk to unacceptable levels for most flight test maneuvers. The recovery system must be fully tested prior to proceeding to these points and these points are clearly "high risk."

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[12] As part of an effort to examine TSM boundaries, several in-compliance weapons delivery patterns were flown with qualified fighter pilots in the front seat of a T-38. In all cases, 4 seconds of TSM resulted in discomfort and no pilot flew to less than 3 seconds of TSM without recovering earlier than planned.

Exception for Operational Maneuvers:

In the USAF Material Command, TSM does not apply to "operationally published maneuvers" flown in accordance with routine procedures. Nevertheless, it remains a valuable tool for understanding the risk of those maneuvers and has been applied to some routine maneuvers to help pilots conceptualize their margin for error.

TSM AND DIVE PLANNING CONSIDERATIONS

Let's examine how TSM consolidates the dive risk assessment problem and provides for increased clarity and efficiency. The examples of figure 3, 6, and 7 may be adjusted to determine the minimum dive recovery initiation altitude required for each maneuver to have the same TSM-measured risk. (Each recovery in the examples was adjusted to provide a constant Mach TSM of 8 seconds.)

The application of TSM to the three dives of figure 3 is depicted in figure 10 (for comparison, the AGL/100 results are depicted to-scale in the lower right-hand corner of the figure. For these dives, the worst-case vector is 90 degrees, resulting in a vertical velocity of approximately 1,600 ft/sec, 900 ft/sec, and 320 ft/sec for the 1.6M, 0.9M, and 180 KCAS dives respectively. Eight seconds of TSM is provided for these recoveries by planning for the recovery to begin at an altitude from which the aircraft can continue the initial vertical velocity for 8 seconds before reaching the minimum altitude for a successful (if barely) 5-g recovery.[13] These three dives now have something in common—the amount of time that the pilot can pause at the worst condition without placing the aircraft into an unrecoverable condition. The TSM method solves the problem of over-conservatism for slow, high N_z-capable aircraft and dangerous under-conservatism for high-Mach aircraft. Under AFFTC TSM guidance, the 180 KCAS aircraft may now operate "routinely" at less than 5,000 feet AGL while the 1.6 MN aircraft must complete a "routine" vertical dive recovery above 15,000 feet AGL. (For the AGL/100 recoveries, the 0.9 MN dive has a very hazardous TSM of just 2.1 seconds, the 1.6 MN dive is definitively unsafe, and the TSM for the 180 KCAS recovery is an

Figure 10 Constant Speed 5-g Recovery Paths with 8 seconds of TSM

extremely conservative 23 seconds.) Altitude at the completion of the recovery varies widely with airspeed, further illustrating how altitude margin is not particularly indicative of the relative risk.

Figure 11 shows the results of applying an eight second TSM to the 0.8 MN varying N_z vertical dive recoveries depicted in figure 6. This figure shows how TSM takes into account that a 1-g increase from 2 g is much more important than a 1-g increase from 8 g; the minimum eight second TSM altitude changes very little for the high-N_z points. Application of TSM produces a relatively constant minimum altitude at the completion of these recoveries because the worst-case dive angle—and thus the altitude lost during the 8 seconds—is the same for each dive. Dive recovery initiation must start higher as recovery N_z is reduced.

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[13] In reality, of course, a constant-speed vertical dive is not likely. The assumption is used here for simplicity but this assumption could not be used for calculating TSM unless the TSM was clearly "routine."
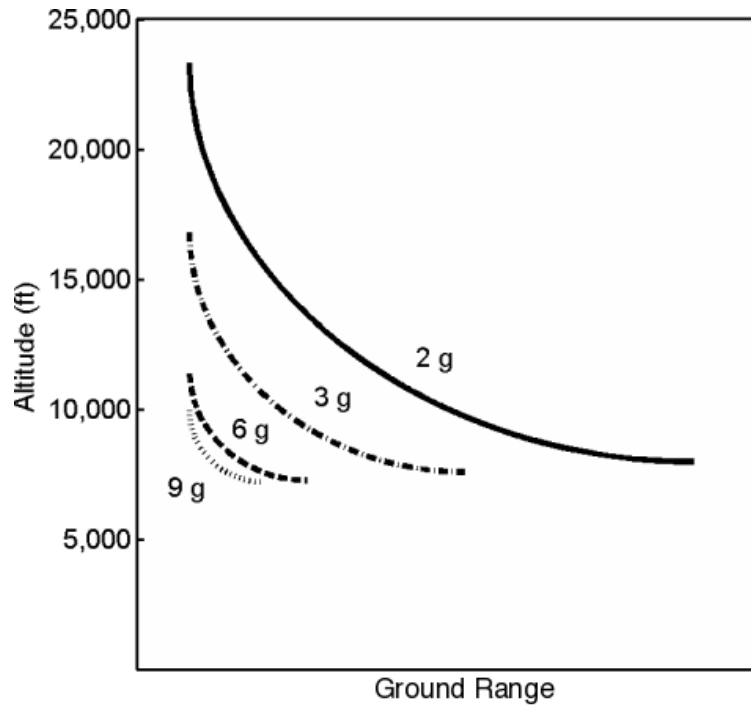
Figure 11 The Effect of N_z on Dive Recoveries with 8 seconds
of TSM

If we compare TSM to a range of dive recovery altitudes determined by the venerable "AGL/100 rule", we can see where this rule is under-conservative—even deadly—and where it is grossly over-conservative.[14] Table 2 shows the TSMs that result from applying the AGL/100 rule for a range of Mach numbers and dive conditions. Note that the TSMs for the typical fighter low-level Mach range (about 0.6 through 0.9) are quite reasonable for routine fighter operations with intensive training and qualifications, but at low Mach numbers the AGL/100 rule is much too conservative and at high Mach numbers use of the AGL/100 rule is dangerous for any dive angle and deadly for steep dive angles. Table 3 depicts the altitude for recovery that would provide 4 seconds of TSM at the same combinations of Mach number and dive angle used in table 2. These results make it clear that there is not a simple rule that works for a wide range of Mach numbers and dive angles.

Table 2 TSM for AGL/100 Rule[15]

TSM for AGL/100 rule		Initial Altitude and Dive Angle			
		4,000 ft AGL -40 deg γ_0	2,000 ft AGL -20 deg γ_0	1,000 ft AGL -10 deg γ_0	500 ft AGL -5 deg γ_0
Mach number	0.3	16.9	16.3	16.4	16.5
	0.6	6.7	7.1	7.5	7.8
	0.9	2.7	3.7	4.3	4.7
	1.2	0.2	1.8	2.7	3.1
	1.5	−1.9	0.4	1.6	2.2

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[14] Regardless of airspeed, the maximum allowable dive angle is determined by dividing the current AGL altitude by 100 (so at 2,000 ft AGL the max dive angle would be 20 degrees)

Table 3 Altitude Required for 4 seconds of TSM[16]

Altitude for 4 seconds of TSM (ft)		Initial Dive Angle			
		-40 deg γ_0	-20 deg γ_0	-10 deg γ_0	-5 deg γ_0
Mach Number	0.3	1,230	590	280	130
	0.6	2,860	1,290	600	280
	0.9	4,860	2,100	940	440
	1.2	7,230	3,010	1,310	600
	1.5	9,950	4,020	1,710	770

Since TSM is determined using the worst-case vector, it is also useful for complex maneuvers. Figure 7 depicted the effect of unloading to roll upright from an inverted 7-g pull as compared to a recovery from the same dive angle with the aircraft already upright. As the aircraft is unloaded while inverted—and for much of the 1-g roll—the dive angle continues to increase. Thus TSM for the inverted case is based on a steeper dive angle, requiring a significantly greater altitude margin to have the desired TSM for the maneuver. Figure 12 depicts the same recoveries as figure 7, but with 8 seconds of TSM for each maneuver. As with earlier examples, the increased vertical velocity results in a higher altitude at the completion of the recovery, but this higher altitude is a result of having the desired safety margin for the worst-case error during the maneuver.

For simplicity's sake, all of these examples assume constant Mach. During an actual dive recovery, the Mach might change drastically. If the TSM is in the "routine" range of at least 8 seconds, it is improbable that changing airspeed will significantly increase the risk of CFIT. When TSM is less than routine, use of the appropriate modeling and simulation—or at least in-flight buildup—will provide the fidelity necessary to understand the effect of any airspeed changes.
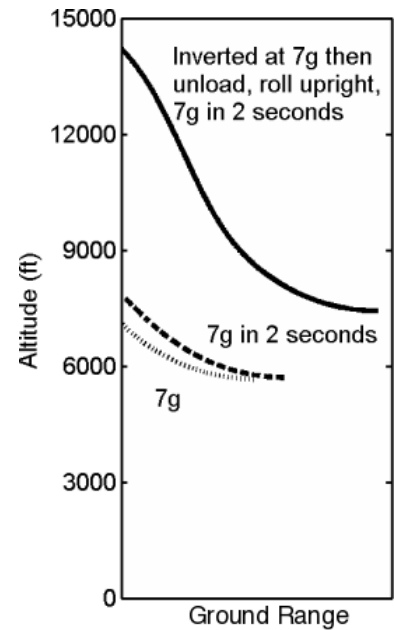
Figure 12 The Effect of Simple Maneuvers on TSM, Normalized to 8 seconds of TSM

SENSITIVITY OF TSM TO INITIAL CONDITIONS AND RECOVERY DEVIATIONS

The validity of TSM is obviously dependent upon how accurately the recovery is flown. Pilots can be late to recover, roll too slowly, use reduced N_z, misinterpret the vertical, set the wrong power, or any number of other errors. Part of TSM planning is understanding the sensitivity of TSM to deviations from the planned entry conditions and recovery method. This information is invaluable when deciding where to focus during the maneuver, whether in the aircraft or in a control room.

In order to examine the sensitivity of TSM to deviations from the planned recovery maneuver, it helps to define a "standard" recovery maneuver. The vast majority of dive recoveries start with an initial condition

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[15] For the sake of simplicity and completeness, the specifications for a particular maneuver that are constant will be given in a footnote. For this table: $-\gamma_0$ = [variable], ϕ_0 = 0 deg, h_0 = [variable], N_{z0} = [as required for constant dive angle], M_0 = [variable], t_d = 0 sec, $\dot{N}_z$ = 3 g/sec, N_{zr} = 5 g, h_S = 0 feet MSL, constant Mach

[16] $-\gamma_0$ = [variable], ϕ_0 = 0 deg, h_0 = [variable], N_{z0} = [as required for constant dive angle], M_0 = [variable], t_d = 0 sec, $\dot{N}_z$ = 3 g/sec, N_{zr} = 5 g, h_S = 0 feet MSL, constant Mach

defined by the aircraft attitude, altitude, airspeed, power setting, and N_z. We will assume that the only rotational rates on the aircraft are from the N_z and the action of gravity and that there is no roll rate or yaw rate at the moment the recovery is initiated. From the initial condition we will assume that some delay is possible with no pilot input to change the aircraft state. Following that delay, the pilot will recover by 1) unloading to achieve an N_z suitable for rolling, 2) rolling to level the wings with a dive angle of less than 90 degrees ("rolling to the nearest horizon"), 3) pulling to the planned recovery N_z, and 4) holding that N_z until the aircraft is no longer descending. The pilot may also adjust the power during the recovery. Obviously, there are far more factors than these that will affect the dive recovery, but they are usually much less important. Let's look at the specifics elements of this dive recovery algorithm one-by-one while assuming that the rest are held constant.

Initial Altitude:

The effect of altitude deviations from the planned minimum recovery altitude are very straightforward. Time Safety Margin is defined by the worst-case vector during the dive recovery. This vector has a vertical velocity component, so in a constant-airspeed dive recovery we can quickly calculate the effect on TSM caused by an altitude deviation by subtracting the amount of time it would take to pass through the deviation at the worst-case vector descent rate. For instance, if we have a planned dive recovery with a TSM vector of -45 degrees at an airspeed of 500 ft/sec, the vertical velocity component is $500 \sin(-45) = -353$ ft/sec. If the dive recovery was begun 700 feet late the planned TSM would be reduced by about $700/353 = 2.0$ sec. Keep in mind that the importance of this change is entirely defined in relation to the original TSM; a 2 second change to a 20 second TSM is almost certainly inconsequential but the same change to a 2 second TSM could be deadly.

Initial Dive Angle:

It seems obvious that steeper dives will reduce TSM. It is not necessarily obvious, though, that this effect is more pronounced for shallow dives.

Let's consider two dives that are flown 10 degrees too steep. For the first dive, let's assume a planned maximum dive angle of 70 degrees; a 10-degree error that results in a 80-degree dive increases the descent rate by a factor of $(\sin(80) - \sin(70))/\sin(70) = 0.048$, or about 5 percent. For the second dive, let's consider the change in descent rate from a 5-degree dive to a 15-degree dive; it is $(\sin(15) - \sin(5))/\sin(5) = 1.97$, or about 200 percent. We can look at the effect on TSM by assuming that the two nominal dives are set up for 8 seconds of TSM at 0.9 MN in a wings-level steady dive and that the pilot reaches 6 g for the recovery at 3 g/sec.[17] In the first case, the dive recovery initiation altitude is about 12,000 feet AGL for a 70-degree dive. If you add 10 degrees to that dive, the TSM decreases to 6.6 seconds. In the second case, the dive recovery initiation altitude is about 800 feet AGL for a 5-degree dive. If you add 10 degrees to that dive, the TSM becomes a very scant 1.4 seconds.

A small error in maximum dive angle is almost meaningless in a near-vertical dive. In a shallow dive at low TSM, a small error can significantly impact the pilot's recovery margin. As always, the smaller the planned TSM, the more significant the effect is for a given deviation.

Bank Angle and Roll Rate:

Bank angle and roll rate errors prior to a dive recovery can increase the dive angle and rate of descent then delay the rotation of the lift vector to the vertical. At 90-degrees angle-of-bank in a shallow dive,

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[17] Constant Mach recovery, sea-level ground, no delay for recovery.

the dive angle ($-\gamma$) is rapidly increasing because the aircraft is accelerating toward the ground at 1 g. For instance, if a pilot rolls to 90 degrees of bank in 300 KTAS level flight at 1 g, the dive will initially steepen at a little less than 4 degrees per second. Table 4 shows how true airspeed and bank angle affect the rate at which the dive angle will increase ($d\gamma/dt$).

Table 4 Gamma Rate (deg/sec) Dependency on Bank
Angle and Airspeed at 1 g[19]

$\dot{\gamma}$ (deg/sec) at $\gamma_0 = 0$ deg, 1 g N_z		Initial KTAS								
		100	200	300	400	500	600	700	800	900
Initial Bank Angle	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	30	1.5	0.7	0.5	0.4	0.3	0.2	0.2	0.2	0.2
	60	5.4	2.7	1.8	1.4	1.1	0.9	0.8	0.7	0.6
	90	10.9	5.4	3.6	2.7	2.2	1.8	1.6	1.4	1.2
	120	16.3	8.2	5.4	4.1	3.3	2.7	2.3	2.0	1.8
	150	20.3	10.2	6.8	5.1	4.1	3.4	2.9	2.5	2.3
	180	21.8	10.9	7.3	5.4	4.4	3.6	3.1	2.7	2.4

Table 4 seems to imply that the slower an aircraft is flying, the more an excessive bank angle will affect the TSM. While an excessive bank angle will cause the descent angle to increase more rapidly at low speed, the recovery N_z will reverse the resulting dive angle more quickly if everything else is held constant. Table 5 shows an example of how TSM is almost insignificantly affected by airspeed at a given initial bank angle. Table 5 also shows how rapidly TSM changes for even slight increases in bank angle around 90 degrees.

Table 5 An Example of TSM Dependency on Bank Angle and
Airspeed at 1 g, 500 ft AGL[21]

TSM at $\gamma_0 = 0$ degs		Mach								
		0.15	0.3	0.45	0.61	0.76	0.91	1.06	1.21	1.36
Initial Bank Angle	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30	>60	>60	>60	>60	>60	>60	>60	>60	>60
	60	>60	>60	>60	>60	>60	>60	>60	>60	>60
	90	40.8	40.7	40.7	40.6	40.6	40.6	40.6	40.6	40.6
	120	18.4	18.2	18.1	18.1	18.1	18.1	18.1	18.1	18.1
	150	9.9	9.7	9.6	9.6	9.6	9.6	9.6	9.6	9.6
	180	6.0	5.7	5.6	5.6	5.6	5.5	5.5	5.5	5.5

The effect of initial bank angle on TSM may not be immediately obvious, aside from how increasing bank angle alone must decrease TSM by either increasing the dive angle, delaying the time to level the wings, or forcing an unload to roll to wings level. The quantity of this effect is closely tied to the intended bank angle. For instance, the TSM for a wings-level dive will not change much for small bank angle changes but at 90 degrees of bank a small bank angle increase can have a major effect. Table 6 shows an example of how quickly TSM may be changing for each degree of bank angle change. For consistency, each condition

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[19] $-\gamma_0 = 0$ deg, $\phi_0 = $ [variable], $N_{z0} = 1$ g, $M_0 = $ [variable], constant Mach

[21] $-\gamma_0 = 0$ deg, $\phi_0 = $ [variable], $h_0 = 500$ feet MSL, $N_{z0} = 1$ g, $M_0 = $ [variable], $t_d = 0$ sec, $\dot{N}_z = 3$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} = 90$ deg/sec, $N_{zr} = 6$ g, $h_S = 0$ feet MSL, constant Mach

of initial bank angle and dive angle defines the start of a recovery from a maneuver ending at 4 g with 8 seconds of TSM. Note that the worst-case situation is in a shallow dive at 90 degrees of bank, but at either a very steep dive angle or very shallow bank angle, the TSM change is inconsequential. Even in the worst case in this example, the TSM is only decreasing by 1 second for every 10 degrees of bank. This is not particularly significant if TSM is greater than 8 seconds, but could be very problematic for low-TSM dives.

Table 6 An Example of TSM Dependency on Bank
Angle and Dive Angle[23]

Change in TSM per degree bank angle change (8 sec TSM Setup)		Initial Dive Angle (deg)			
		10	30	60	80
Initial Bank Angle (deg)	15	-	−0.02	-	-
	45	−0.02	−0.02	−0.02	-
	90	−0.10	−0.06	−0.02	−0.02
	135	−0.08	−0.04	−0.02	−0.02
	165	−0.04	−0.02	−0.02	-

The effect of roll rate on TSM is obviously dependent upon the amount of rolling that is required. Tables 7 and 8 show two examples of the change in the minimum altitude to start an 8 second TSM dive recovery for a variety of bank angles and roll rates when the aircraft is at 4 g at the start of the recovery.

Table 7 An Example of TSM Dependency on Roll
Rate and Bank Angle for a Shallow Dive[25]

Alt (ft) req'd for 8 sec TSM $\gamma_0 = -5$ deg, $M_0 = 0.8$ MN		Initial Bank Angle (deg)			
		45	90	135	180
Roll Rate (deg/s)	180	640	670	940	1,450
	90	650	690	1,240	2,340
	45	650	730	1,900	4,360
	30	650	770	2,630	6,610
	15	650	880	5,200	13,740

A few things about roll rate are obvious. First, the faster the roll rate, the less the initial bank angle matters. Second, if the initial bank angle is shallow the roll rate doesn't matter; the shallower the bank, the less the roll rate can affect the dive recovery. The tables demonstrate how, as bank angle increases to a maximum of 180 degrees and the dive angle shallows (with initial positive N_z), the roll rate becomes increasingly important. For example, if 90 degrees per second of roll rate is planned for the conditions of the shallow dive on table 7 and the actual roll rate is 45 degrees per second, the dive recovery altitude for 8 seconds of TSM almost doubles (from 2,340 feet to 4,360 feet).[28]

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[23] $-\gamma_0 =$ [variable], $\phi_0 =$ [variable], $h_0 =$ [as required for 8 sec TSM], $N_{z0} = 4$ g, $M_0 = 0.8$ MN, $t_d = 0$ sec, $\dot{N}_z = 3$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} = 90$ deg/sec, $N_{zr} = 6$ g, $h_S = 0$ feet MSL, constant Mach

[25] $-\gamma_0 = 5$ deg, $\phi_0 =$ [variable], $h_0 =$ [as required for 8 sec TSM], $N_{z0} = 4$ g, $M_0 = 0.8$ MN, $t_d = 0$ sec, $\dot{N}_z = 3$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} =$ [variable], $N_{zr} = 6$ g, $h_S = 0$ feet MSL, constant Mach

[27] $-\gamma_0 = 70$ deg, $\phi_0 =$ [variable], $h_0 =$ [as required for 8 sec TSM], $N_{z0} = 4$ g, $M_0 = 0.8$ MN, $t_d = 0$ sec, $\dot{N}_z = 3$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} =$ [variable], $N_{zr} = 6$ g, $h_S = 0$ feet MSL, constant Mach

[28] The reduction in roll rate needn't be caused by pilot error. Load alleviation systems or unexpected aircraft flying qualities can unexpectedly reduce the roll rate. Needless to say, this is not something you want to discover during the dive recovery.

Table 8 An Example of TSM Dependency on Roll
Rate and Bank Angle for a Steep Dive[27]

Alt (ft) req'd for 8 sec TSM $\gamma_0 = -70$ deg, $M_0 = 0.8$ MN		Initial Bank Angle (deg)			
		45	90	135	180
Roll Rate (deg/s)	180	10,910	11,330	12,000	12,530
	90	11,050	11,640	12,560	13,430
	45	11,330	12,260	13,650	15,200
	30	11,610	12,870	14,750	16,940
	15	12,460	14,720	18,000	22,040

Bank angle and roll rate interact in complex ways to affect TSM. Roll rate is particularly problematic because it is part of the recovery, not part of the recovery decision. The most conservative approach is to set bank angle and roll rate limits that are significantly steeper or slower than expected. Any error, pilot or otherwise, would ideally tend toward shallower bank angles and faster roll rates. For instance, if an aircraft is limited by the flight control system to 360-degrees-per-second roll rate, it would be unwise to assume that the pilot will achieve that roll rate during the recovery unless the bank angle was so shallow it didn't matter; any error would result in reducing the actual TSM. Roll acceleration must also be considered; the time to get to the desired roll rate then stop it will increase the time to achieve wings-level flight. Dive angle, as part of the recovery decision, is easier to set as a limit but care must still be taken to ensure that the planned maximum dive angle for recovery initiation is observed.

Airspeed/Mach and Power Setting:

If the airspeed at the initiation of the recovery is different than planned, the effect on the recovery depends on several factors; sometimes a faster airspeed will improve the TSM, sometimes it will reduce the TSM. The most obvious effect is the one produced by increasing the speed and descent rate at the worst-case vector that defines TSM. If everything else is held constant, a faster airspeed will result in reaching the minimum recovery altitude faster and produce a lower TSM. Additionally, the airspeed can significantly affect the turn radius of the aircraft, thus changing the altitude lost during the recovery.

Figure 13 illustrates the effect of equivalent airspeed—the airspeed equivalent to a constant dynamic pressure—and dive angle on the instantaneous turn radius for a wings-level dive recovery. The corner speed marks the point where the limit AOA provides the limit N_z. For this analysis, we will consider the corner speed to be the speed at which the planned recovery N_z meets the lift limit. Above the corner speed the turn radius is roughly the same regardless of dive angle, provided the intended N_z is significantly greater than 1 g. As the equivalent airspeed slows, the turn radius increases, asymptotically approaching the airspeed needed to maintain the N_z required to hold the specified dive angle at the constant AOA. For level flight, the aircraft must hold 1 g to maintain the level flight path. The speed that corresponds to 1 g at the pullout AOA defines the asymptote that the turn radii approach from higher and lower airspeeds. In a 60-degree dive, the aircraft must hold 0.5 g to maintain the dive angle. The airspeed required to maintain 0.5 g at the pullout AOA is much less than for 1 g, so the asymptote is at a lower airspeed. In a vertical dive (90-degree dive) the instantaneous turn radius is the same for a given AOA regardless of airspeed. For non-vertical dives, the airspeed below the asymptote will produce an N_z insufficient to hold the current dive angle so the nose will fall; this is signified by a negative turn radius.

The effect of an airspeed error on the recovery conditions depends on the rest of the recovery conditions. If the planned recovery airspeed is significantly higher than the corner airspeed for the planned g, recovering
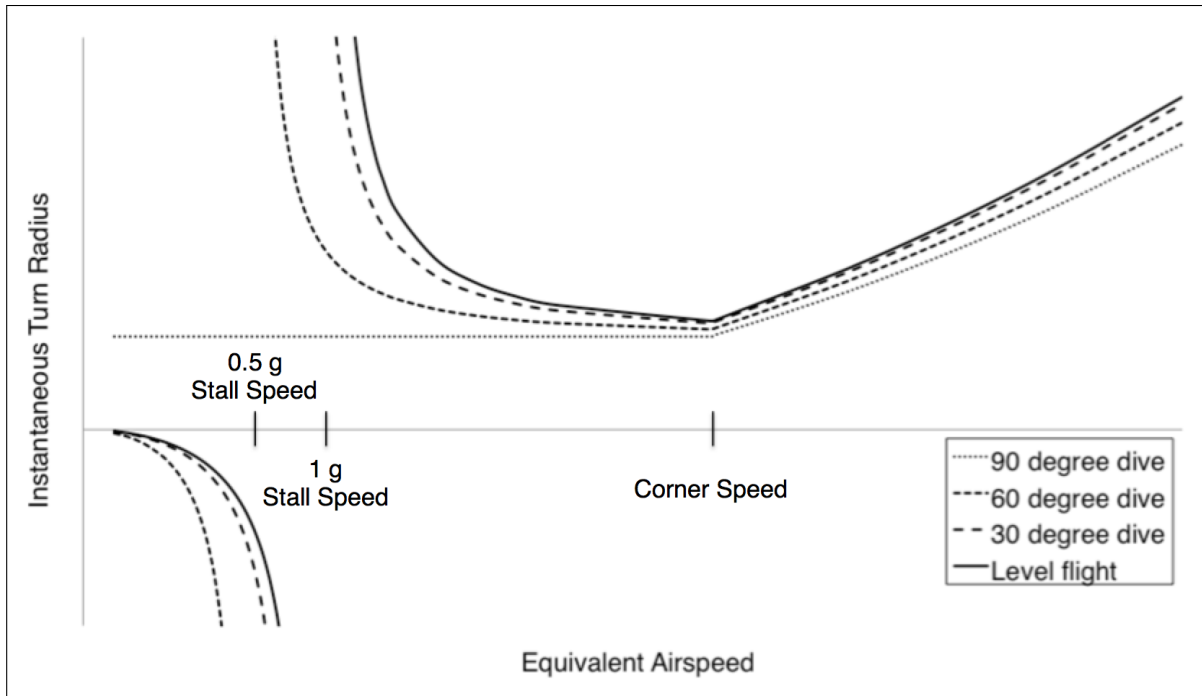
Figure 13 The Effect of True Airspeed on a Constant-AOA/7-g Limited Wings-Level Pull

at a faster airspeed than planned will increase the turn radius and decrease the TSM. On the other side of the airspeed spectrum, if the recovery is planned to occur at an airspeed close to the 1-g stall speed, decreasing the recovery speed will significantly increase the turn radius and altitude lost during the recovery (maybe even making recovery at that speed impossible). This will significantly decrease the TSM. Between these two extremes, the interaction between the TSM vector time and the altitude lost during the dive recovery will be highly dependent upon the specific characteristics of the aircraft and the planned recovery technique.

With reduced TSM, it is important to err on the fast side for recoveries close to stall speed and on the slow side for recoveries above the corner speed; everything else is dependent on the aircraft and the planned recovery.

Calibrated and equivalent airspeed are very close for dive recovery computations where compressibility is not a significant factor (altitudes near sea level). Mach number, on the other hand, increases for a given equivalent/calibrated airspeed as the altitude increases. Depending upon the aircraft, transonic and supersonic Mach numbers can have a significant effect on the N_z available for dive recovery; this tends to complicate very high speed dive recoveries.

The primary effect of thrust setting is in how it changes the airspeed during the recovery. There are secondary effects, such as thrust vectoring, that are highly dependent on aircraft type and recovery technique. In general, though, a higher-than-planned thrust setting will tend to decrease TSM unless the airspeed is close to the stall speed at recovery. Except for slow speed recoveries, it is good practice to use a low thrust setting for recovery. As TSM decreases below 8 seconds, it will be important to know the thrust setting that will be required and ensure that any deviations from that setting are in the safer direction so that they will increase, not decrease, TSM.

Engine thrust characteristics are highly dependent on Mach number, altitude, and airspeed. Many modern engines operate at relatively high power settings when in "idle" power at high airspeed—it is not unusual

for a modern fighter engine to be in full military power in supersonic flight in spite of having a throttle setting below military power. Pulling the power levers all the way to minimum might not decrease the engine power enough to reduce the airspeed in a dive. This can cause significant additional altitude loss and reduced TSM if the airspeed is above the corner speed.

Aircraft Configuration and Weight:

Aircraft configuration and gross weight can significantly affect a diving maneuver, mostly by changing the stall speed and the corner speed. For instance, if a low-speed diving test point was planned for a light-weight aircraft but mistakenly flown in a heavy-weight aircraft, the TSM could be dangerously reduced or dive recovery made entirely impossible. Increased weight will increase the stall speed, decrease the corner speed, and increase the turn radius. Additional drag will slow the recovery airspeed if additional thrust isn't available. If lifting devices (flaps, slats, etc.) are planned for the dive recovery but inadvertently not deployed, dive recovery may be severely compromised.

Configuration and gross weight may have to be tightly controlled when planning for a low TSM. If the objectives allow, it is a good idea to define allowable ranges for aircraft weight and drag so these parameters may be adjusted during maneuver planning to increase TSM.

Cockpit N_z and N_z Onset Rate:

The most obvious effect that an N_z error will have at the start of the recovery will be in the initial dive angle. If the aircraft is upright (less than 90-degrees bank angle) excess N_z will decrease the dive angle prematurely and improve the TSM. Conversely, an aircraft in inverted flight (more than 90-degrees bank angle), excess N_z will increase the dive angle before the recovery and reduce the TSM.

The N_z onset rate will have roughly the same effect as N_z errors by increasing or decreasing the time at an unplanned N_z. There might be second-order effects as well, such as a too-slow reduction in N_z while unloading to the N_z required for a rolling maneuver. For bank angles that are causing the dive angle to increase, anything that slows the progress of the aircraft lift vector toward the zenith will decrease the TSM.

Sensitivity to Unplanned Delay Prior to Recovery Initiation:

The sensitivity to unplanned delay is almost entirely a function of the descent rate and the rate at which the descent rate is changing at the end of the planned delay time. The effect on TSM is much less pronounced if the aircraft is pitching up (dive angle decreasing) during the planned procedure than if the aircraft is pitching down (dive angle increasing).

Unplanned delay is a particularly interesting error because it is measured the same way that TSM is; it is measured in time. Unlike the various conditions that define the recovery initiation point such as dive angle, bank, and airspeed, unplanned delay necessarily occurs *after* the recovery should have started. For instance, if the dive angle exceeds the maximum planned dive, the "Abort!" call will probably come before the minimum altitude. Unplanned delay comes after the planned point for TSM calculation, where—if the conditions are such that TSM is rapidly decreasing—TSM will rapidly decrease below that expected for the maneuver, and may even decrease to the point that recovery is impossible in much less time than the planned TSM.

The most important weakness in the original TSM methodology was the complete dependency on re-covery being initiated immediately upon the achievement of the procedure limitations. Test teams were

completely aware that some maneuvers could produce dangerous TSMs if the pilot delayed recovery only slightly more than planned, yet the only available response was to be especially diligent about ensuring the recovery started without added delay. Several surprises have demonstrated that this is not enough. Unplanned delay is a risk element that must be accounted-for in the TSM planning. Delayed Time Safety Margin provides a numerical solution that allows for calculation of an adjusted TSM to account for unplanned recovery delay.

DELAYED TIME SAFETY MARGIN (DTSM)

Unplanned Recovery Initiation Delay:

As TSM was employed across AFMC—and especially at the 412 TW and AFTC—it became apparent that there were circumstances where TSM did not adequately capture the time the test team and test pilot had available for errors. It worked quite well for cases such as steady wings-level dives and procedures that ended with the dive angle remaining the same or shallowing, but TSM did not seem to capture the actual dive recovery risk of the procedures like a split-s or wind-up turn where the procedure ended while the dive angle was increasing. For these procedures, if the entire procedure and recovery was flown exactly as planned, the TSM made a lot of sense, but if the pilot delayed the recovery by just a second or two the TSM would rapidly decrease. For instance, it is possible for a split-s maneuver with 8 seconds of TSM to become unrecoverable after just a few seconds of delay past the intended recovery initiation point. Time Safety Margin did not adequately address an unexpected delay in the start of the recovery.

Definition of Terms for DTSM:

It is a good practice to include a reaction delay time as part of the planned procedure,[29] but exceeding the planned delay may rapidly reduce the TSM so the implications of exceeding the planned delay time must be understood. Figure 14 depicts the same flight path as figure 8 (Basic Dive Recovery Terminology), but with the addition of the "delayed procedure" and the "delayed recovery start" point. This potential source of delay will be very useful for adjusting TSM when the descent angle is steepening at the end of the procedure.[30]

- "Unplanned delay"—The length of time in seconds between the expected recovery start and the delayed recovery start. This time does not include the planned delay prior to the expected recovery start.
- "Delayed recovery start"—The point at which the recovery is actually started if there is unplanned delay.
- "Delayed procedure"—The flight path of the aircraft during the time between the expected recovery start and the delayed recovery start. This flight path will typically continue the conditions of the expected recovery start point, including bank angle, N_z, $\dot{N}_z$, and so on.

As with no unplanned delay, the worst-case vector can occur at any point during the maneuver, from the start of the procedure to the end of the recovery. Figure 15 depicts a case resulting from a split-s procedure where the recovery is initiated in a steep inverted dive. Note that the worst-case vector occurs after the roll to upright; this is significantly after the start of the delayed recovery. In this example, the continued maneuver only includes the dive pull-out after the roll to upright is complete.

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[29] The duration of this delay would be a function of the means by which the terminate or abort criteria are determined and relayed. It might be a few tenths of a second when a verbal count-down is used or a few seconds if the test team is likely to be surprised by the abort call.

[30] The section of this report entitled "Delayed Time Safety Margin" deals with this issue in depth.
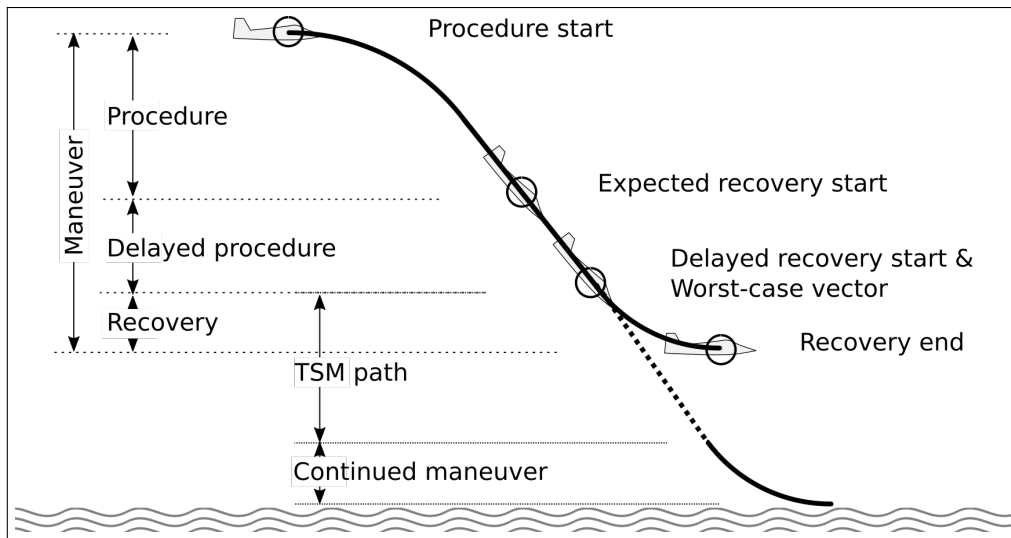
Figure 14 Dive Recovery Terminology for to a Wings-Level Dive with Unplanned Recovery Delay
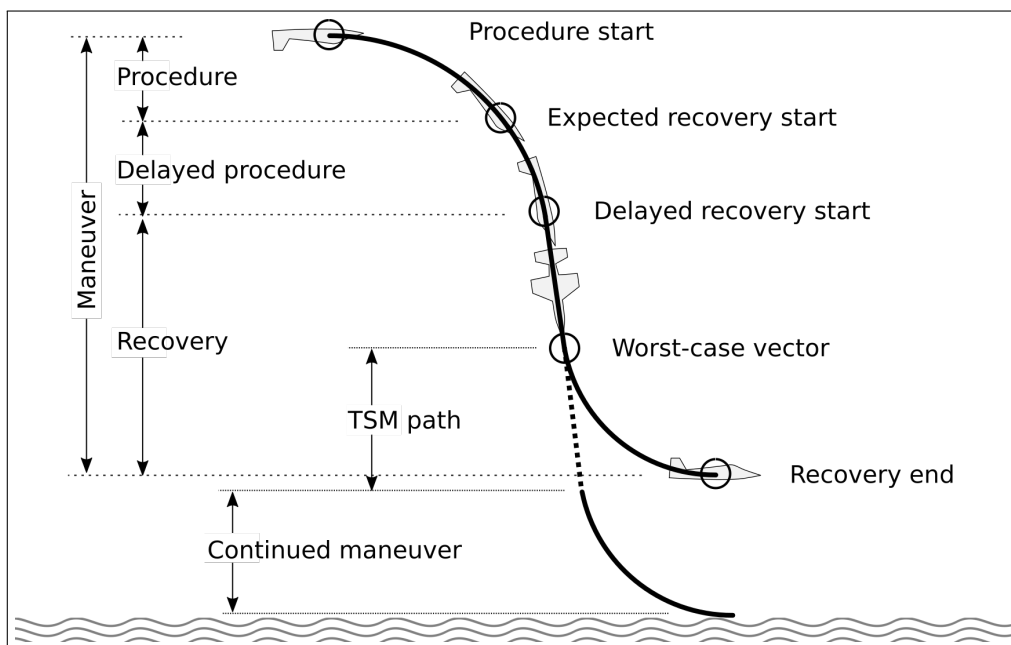
Figure 15 Dive Recovery Where the TSM Vector Occurs after the Start of the Recovery

On the other end of the spectrum, figure 16 depicts a case where the procedure begins in an inverted climb with a split-s and continues through the split-s until stabilizing in an upright dive prior to the expected start of the recovery. Note that the worst-case vector occurs during the procedure, not the recovery, so the TSM path is vertical and the continued maneuver includes about half of the procedure and all of the delayed procedure and recovery. In this case, unplanned delay will not change the worst-case vector.
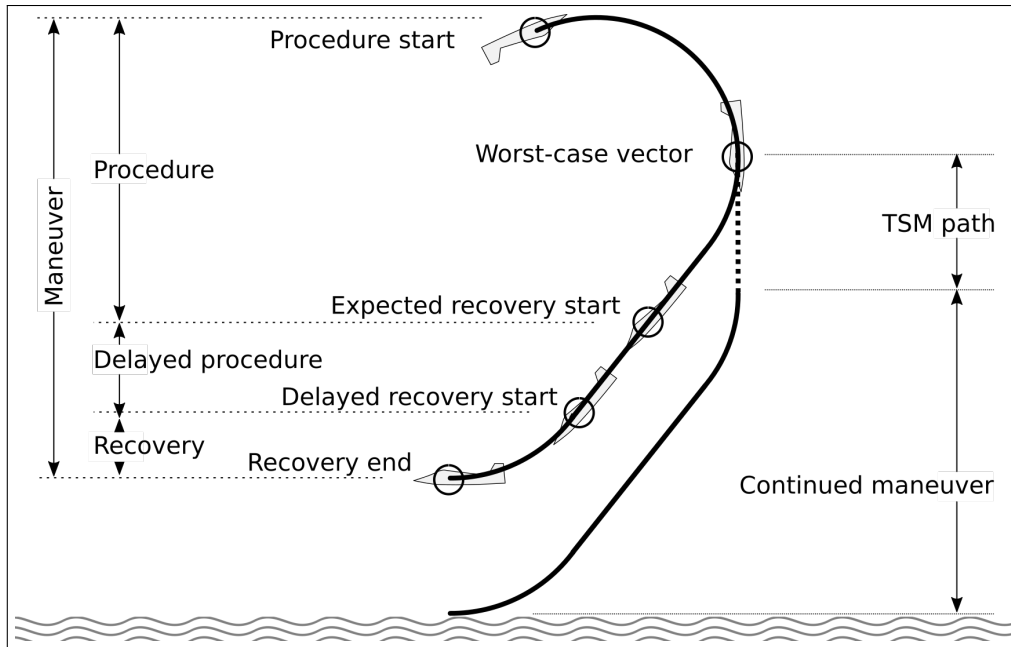
Figure 16 Dive Recovery Where the TSM Vector Occurs during the Procedure

Calculating DTSM:

To understand the possibly hazardous effect of unplanned delay past the intended recovery condition, let's look at a procedure that results in a rapidly increasing dive angle at the expected recovery start. Figure 17 illustrates just such a procedure: a split-s maneuver. The figure depicts the intended maneuver with no unplanned delay and two examples of the maneuver with unplanned delay. The intended maneuver is an inverted pull from level flight to a dive angle of 45 degrees. Upon reaching that dive angle, the pull is relaxed and the aircraft is rolled upright; the worst-case vector occurs during this roll. Once the wings are level, the recovery N_z is set and level flight is quickly attained. In the figure, this path is shaded black, with a black circle labelling the expected recovery start with no unplanned delay. The red and blue paths, each labeled with a delayed recovery start (1 and 2) depict two examples of unplanned delay and the resulting recovery maneuver. These maneuvers assume that the pilot will recover in accordance with typical nose-low recovery techniques, using the same roll rates, N_z rates, and recovery N_z as intended for the expected recovery. For the first (red) unplanned delay, this means a maneuver similar to the intended recovery maneuver but starting both lower and steeper. The second (blue) unplanned delay results in the aircraft being upright when the delayed dive recovery is begun so there is no need to unload or roll and the pilot just pulls to the recovery N_z. The dashed lines embedded in the three maneuvers represent the TSM paths along their respective worst-case vectors.

The effect on TSM of delaying the recovery is immediately clear. With no delay, the dive angle is relatively shallow and the TSM path starts from a higher altitude. With the first delay increment (the red path), the unplanned delay steepens the worst-case dive angle, reduces its altitude, and requires additional altitude for the recovery. The second delay increment passes through the vertical during the delay so the worst-case vector is that vertical dive. For this maneuver, additional delay rapidly reduces the TSM until the aircraft passes through the vertical, at which point the TSM begins to increase slightly.

The TSM paths are gathered on the right side of the figure to allow easy comparison of their length. Assuming that the true airspeed is constant, it is apparent that the short delay from the expected recovery
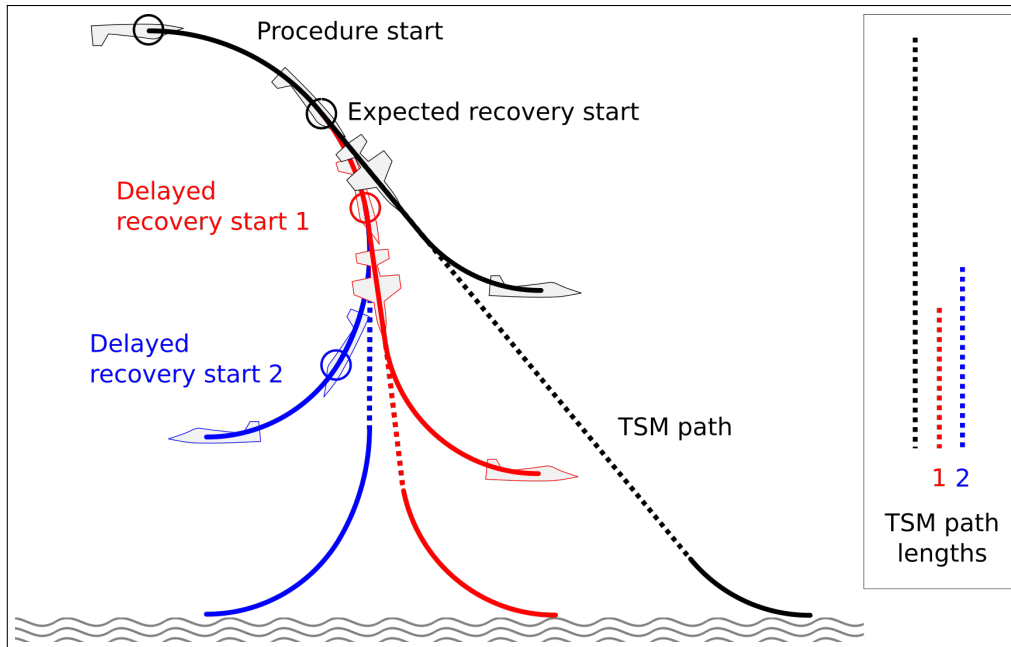
Figure 17 Dive Recovery with Unplanned Delay

start to the first delayed recovery start decreased the TSM by about 70 percent. Although the TSM increased a bit with when the unplanned delay resulted in pulling through the vertical prior to the start of the recovery, it is still less than half of the TSM expected for the maneuver without unplanned delay.

Before we go on, some definitions are in order.

- "Instantaneous TSM (ITSM)"—The TSM for a complete maneuver, including the effects of any unplanned delay.

- "Delayed TSM (DTSM)"—The TSM for a maneuver found by adding the unplanned delay to the ITSM. DTSM may be thought of as the sum of the two predominant sources of time delay in a maneuver; time delay at the worst possible point in the maneuver for adding delay (the worst-case vector), and unplanned time delay at the end of the procedure (where delay is most likely to occur).

$$DTSM = ITSM + Unplanned Delay$$

Let's return to figure 17 for an example of calculating DTSM. For the sake of simplicity, assume that the true airspeed remains constant throughout the three example maneuvers; this will allow the presentation of unplanned delay, ITSM, and DTSM using the flight path lengths. Figure 18 depicts these times graphically for each of the maneuvers in figure 17. The DTSM provides a measure of the total time available for delay, captured by adding the unplanned recovery delay and the resulting ITSM. The no-unplanned-delay case shows the best case for ITSM, but any delay in initiating the recovery rapidly reduces the ITSM. The first delay increment, shown in red, results in a severe reduction in ITSM but this is mitigated somewhat by the time of the unplanned delay; it takes time to get to this low ITSM and this time is available as margin prior to the start of the recovery. The second increment of unplanned delay, shown in blue, results in slightly more ITSM than the first increment. When the unplanned delay time is added, the DTSM is greater than that for the original maneuver. This indicates that, for this particular procedure, the safest way to avoid ground impact might be to just continue the pull all the way around to level flight; the pilot is far less likely to delay the recovery when the recovery is nothing more than continuing the original procedure. These examples

only represent three points on a curve where the independent value is the unplanned recovery time and the dependent value is the DTSM. If DTSM is used to calculate an overall TSM, the TSM is the minimum value of DTSM across this curve. (See figure 22 for an example of a complete DTSM curve for a similar maneuver.)
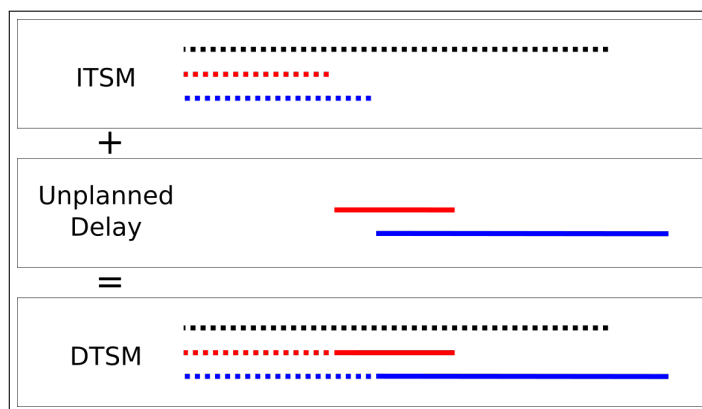
Figure 18 Calculation of DTSM from Figure 17

When DTSM is included in the computation of TSM, TSM is the minimum DTSM for the full recoverable range of unplanned delay. The unplanned delay starts at 0 seconds and ends either when the unplanned delay results in a recovery prior to initiation of the planned recovery (think of a split-s procedure that continues at the initial N_z until a climb is achieved) or when the unplanned delay results in no ground collision margin. Using DTSM to calculate overall TSM, a TSM of 4 seconds could mean "Recovery as planned has a TSM of 4 seconds" or "Delaying the recovery by more than 4 seconds will result in ground impact during the recovery." It could also mean "Delaying the recovery by 1 second results in an ITSM of 3 seconds." So long as the sum of the unplanned delay and the ITSM for that unplanned delay is the minimum value across the full range of available unplanned delay, the TSM is the margin of safety with respect to time. Test teams should express TSM in a way that captures the amount of unplanned delay added for the TSM as part of the final TSM presentation, e.g., "The TSM for the maneuver is 4 seconds including 1 second of unplanned delay at initiation."

Delayed Time Safety Margin captures the additional risk of unplanned delay as part of the final TSM value, making it reasonable to use standard TSM guidance. The additional effort required to determine a valid DTSM profile is only justified when consideration of DTSM would change the final TSM result. An examination of how DTSM changes with unplanned delay for a variety of diving maneuvers will show that DTSM is only a factor if the dive angle is increasing at the expected recovery start; if the dive angle is steady or decreasing the DTSM should not decrease with unplanned delay.

DTSM Examples:

The following examples show the TSM implications for most dive recovery situations. These examples assume that the N_z and bank angle of the aircraft remain unchanged during the unplanned delay. *If a test procedure ends with a non-zero roll rate and/or N_z rate, it is prudent to use the worst-case overshoot of these parameters as part of the worst-case conditions used to determine TSM.* Failure to do this could result in a much higher dive angle rate-of-change during any unplanned delay, leading to a much lower minimum DTSM than expected.

DTSM in an Upright Steady Dive.

The simplest form of TSM stays simple for DTSM. In a steady dive with a constant dive angle and airspeed, the worst-case vector corresponds to the point just prior to the addition of N_z for recovery. The TSM vector is the vector of the steady dive, so unplanned delay just keeps the aircraft on that vector. In a steady dive, the TSM decreases by one second for every second of unplanned delay and the DTSM remains constant as unplanned delay is added.

Figure 19 depicts how ITSM and DTSM change over time for a steady dive. As unplanned delay time is added, the ITSM decreases at one second per second until the ITSM is nil. Adding the unplanned delay time to the resulting ITSM produces a constant DTSM, so DTSM need not be used to determine TSM.
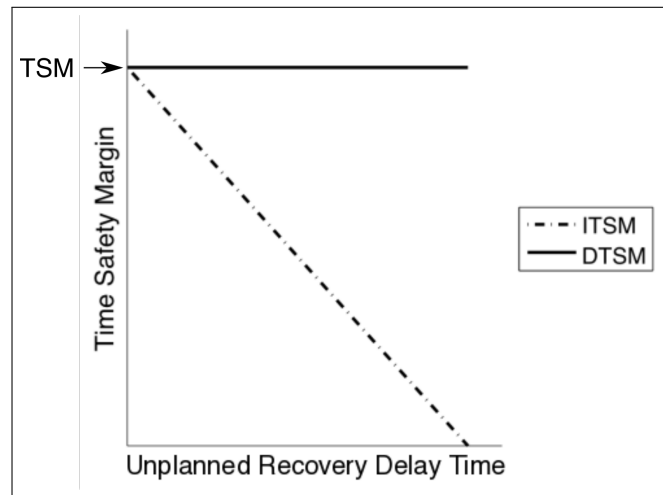
Figure 19 ITSM and DTSM Changes for a Steady Dive

Things become a little more complicated if power effects are taken into account. If the airspeed is increasing just prior to starting the recovery, any unplanned delay in the recovery will result in increased airspeed for the pull-out which, in turn, decreases the time to an unrecoverable condition by increasing the turn radius and getting there more quickly. DTSM, however, will remain unchanged so long as the increasing airspeed is accounted for in the TSM-defining vector to the last possible recovery initiation point.[31]

In an upright steady dive the safety margin remains the same regardless of whether the pilot inadvertently delays recovery or delays at the worst-case vector. This is obvious, of course, since the worst-case vector and the TSM vector are the same. DTSM is never less than the ITSM for no unplanned delay, so the TSM need not consider unplanned delays.

DTSM in an Upright Wings-Level Pull.

If the beginning of the dive recovery is marked by a wings-level pull that produces a steadily-decreasing dive angle, the effect on ITSM, DTSM, and the overall TSM is dependent on how the N_z will be changed for the recovery.

Figure 20 shows the three basic possibilities for this recovery. In the first case, the recovery N_z is less than the procedure N_z. In the second, the recovery and procedure N_z are the same. The third case shows what happens when the recovery N_z is greater than the procedure N_z.

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[31] Accounting for thrust effects requires excellent modeling and simulation.
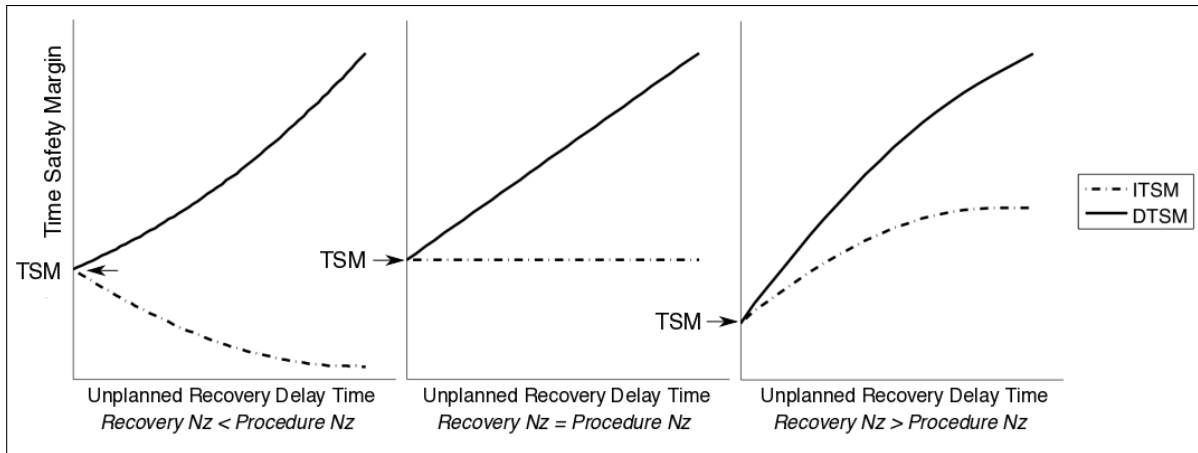
Figure 20 ITSM and DTSM Changes for a Wings-Level Dive Pullout Starting with a Decreasing Dive Angle

The first case is the more conventional case; the diving procedure is at substantially less N_z than the planned recovery N_z, so at the completion of the test point the N_z will be increased for the recovery. In this case, delaying the recovery increases the altitude lost and decreases the ITSM. Nevertheless, if the N_z during the wings-level procedure is sufficient to decrease the dive angle, the ITSM will not be decreasing faster than one second per second so the DTSM will be constantly increasing. Thus, the overall TSM is the ITSM with no unplanned delay; DTSM need not be considered.

We saw that the DTSM remained the same for a steady dive, but when the wings-level pull during the procedure is not changed for the recovery the ITSM remains the same and the DTSM steadily increases. This makes sense because the maneuver does not change with the delay. The overall TSM is the ITSM with no unplanned delay; DTSM need not be considered.

If the recovery N_z is less than the procedure N_z (as might be the case if the procedure N_z is high enough to warrant minimizing exposure to g-induced loss of consciousness (GLOC), any unplanned delay will improve the ITSM. In this case, the ITSM line starts with a positive slope and curves upward until the unplanned delay time results in a recovery prior to the start of the actual recovery. Even though the ITSM and DTSM are constantly increasing during a maneuver like this, the overall TSM would remain the ITSM for no unplanned delay because that would be the minimum DTSM for the recovery.

What does it take for the DTSM to decrease in a wings-level dive—for things to get worse with unplanned delay? We have seen that DTSM remains constant in a steady dive with a constant dive angle and that DTSM will always be increasing when the dive angle is decreasing. All that is left to consider is when the dive angle is increasing at the planned start of the recovery.

DTSM in an Upright Wings-Level Push.

It is not uncommon to target an N_z less than 1 g during flight test. Sometimes the most convenient way to get there is from a wings-level push. These test procedures typically result in a dive. What does this mean for TSM?

Figure 21 depicts how ITSM and DTSM change for a wings-level push starting in a slight dive and at an altitude that is low enough that inadvertently delaying the push will eventually result in an unrecoverable dive. In this situation, the TSM-defining worst-case vector occurs in a steeper dive and at a lower altitude

the longer the recovery is delayed; this results in steadily-decreasing ITSM and DTSM.[32] In this case, the TSM for the dive would be the DTSM corresponding to the unplanned delay time that results in an ITSM of 0 seconds.
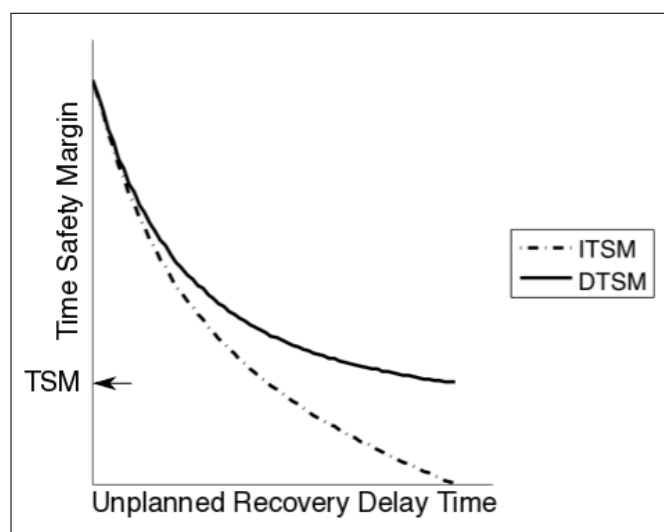
Figure 21 ITSM and DTSM for a 0-g Unload from a
Shallow Dive

Wings-level push-over procedures can be deceptively risky thanks to the very rapid decrease in ITSM with recovery delayed. Imagine a procedure flown at relatively low altitude—perhaps to achieve a high dynamic pressure ($\bar{q}$)—designed to be at -1 g in level flight by starting the procedure from a slight climb. If a dive is never attained during the test point no dive recovery is required, ITSM is not defined, and all appears well. But if the pilot is slow to achieve the N_z, stays there too long, or exceeds the planned N_z, the ITSM will be decreasing rapidly as soon as the aircraft enters a dive.[33]

DTSM in an Abbreviated Split-S.

A full "split-s" aerobatic maneuver starts in inverted level flight and ends in upright level flight. The pilot rolls inverted and pulls through the vertical until the aircraft is back in level flight. This procedure is relatively trivial with regard to TSM since the maneuver includes the recovery; there is no place to add delay other than at the worst-case vector so DTSM doesn't apply. But this simplicity comes at the cost of altitude and energy loss—something most test teams are hesitant to accept unnecessarily.

In flight test, a split-s maneuver is typically an abbreviated form of the aerobatic maneuver. By trading potential energy (altitude) to maintain kinetic energy (airspeed), it is possible to stabilize for a few seconds on an airspeed or Mach number that could only otherwise be transited very quickly. In order to minimize energy loss, a flight test split-s procedure is typically stopped far short of the vertical and a routine dive recovery maneuver is accomplished to minimize altitude loss, energy loss, and risk.

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[32] The curve shallows as the dive angle increases because the effect of gravity is decreasing and the vertical velocity is changing less for each degree of added dive angle. If the push is between 0 g and 1 g, the dive angle will stop increasing as the dive angle coincident with that N_z ($N_z = \text{g} \cos \gamma$) is approached. Once this happens, the DTSM remains constant and the ITSM changes at one second per second because the aircraft has achieved a steady-state wings-level dive.

[33] As an instructor pilot at the USAF Test Pilot School, the author has seen many students attempt to set a $-N_z$ point from wings-level flight or a slight climb; the rate at which the dive angle builds often seems to come as a surprise.

Figure 22 depicts the progression of ITSM and DTSM for a split-s procedure as unplanned delay is added past the planned recovery dive angle. This particular procedure is designed to be flyable all the way through the vertical and back to level flight like an aerobatic split-s; this is indicated by the ITSM remaining greater than zero. (If the split-s procedure would result in an unrecoverable condition if continued past the planned recovery conditions, the ITSM would terminate at zero and the figure would look much like figure 21.)
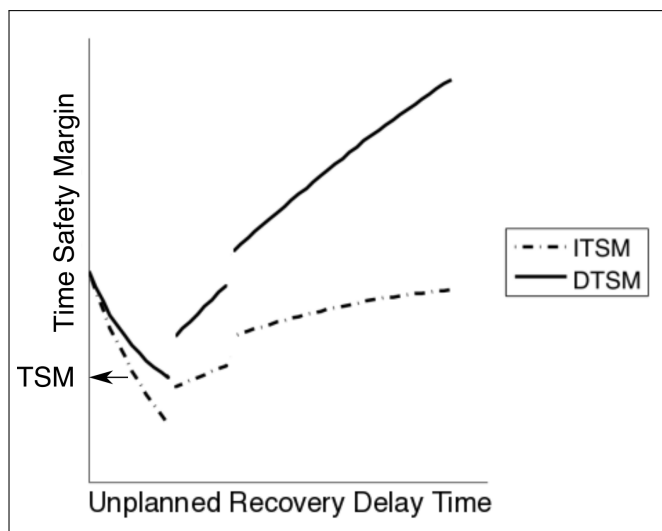
Figure 22 ITSM and DTSM Changes for a Short-Term
Split-S Procedure

This figure has some discontinuities that divide it into distinct time periods. These are the result of assumptions about how the pilot will accomplish the recovery based on the conditions at which the recovery is started. The first unplanned delay time period depicts when the recovery requires a 180-degree roll to the "nearest horizon" after unloading to the rolling N_z. In the third time period, the unplanned delay has caused the aircraft to pass the nadir before the recovery is started so the pilot just adjusts the N_z to the recovery N_z and continues the pull until the recovery is complete; not having to unload to rolling N_z and roll upright saves a lot of time and altitude. The middle time period corresponds to where the aircraft passes the nadir while the pilot is unloading to the rolling N_z then, with no roll required, just increases the pull to recovery N_z.[34] For this example, the minimum DTSM occurs at the end of the first time period; if DTSM were used to determine TSM for the maneuver, the TSM would be the minimum DTSM as this is the worst case for added delay.

This example shows how sensitive TSM computations are to the planned and actual maneuver execution. It might be reasonable to trade a little TSM to keep the maneuver simple and lower the potential for planning mistakes or execution errors.

When the Worst-Case Vector Occurs Before the Unplanned Delay is Complete:

Delayed Time Safety Margin may be calculated for the entire range of unplanned delay that does not result in a recovery prior to the end of the unplanned delay. In those recoveries that begin with the dive angle moving toward the horizon, the worst-case vector will not change with the addition of delay. Calculating

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[34] The recovery model used for this simulation assumes that once the pilot starts to unload to rolling N_z he will not notice whether or not the aircraft has passed the nadir until the unload is complete.

DTSM for these cases is not necessary because unplanned delay will not decrease the ITSM by more than one second per second of delay. Figure 20 depicts three dives where the climb angle is moving toward the horizon at the planned start of the recovery; the difference is the relationship to the recovery N_z and procedure N_z. In these cases, the ITSM is increasing more rapidly than the DTSM unplanned delay is added. This may be seen as yet another good reason to try to complete test procedures with the dive angle stable or moving toward the horizon.

In a maneuver that starts with the dive angle moving away from the horizon, at some point during the unplanned delay (assuming that the maneuver is not interrupted by the ground) the dive angle will probably pass through a point of maximum steepness.[35] This is typical of split-s maneuvers. If the unplanned delay is long enough for the aircraft to pass through the nadir, additional delay past that point will aid the recovery. Figure 22 depicts the change of ITSM and DTSM for the entire range of unplanned recovery delay time, terminating where the unplanned delay results in a completed recovery. For this example, the worst-case vector stops changing just prior to the end of the second segment.

Does the Ratio of Unplanned Delay and ITSM Matter for the Overall TSM?:

When unplanned delay prior to the recovery is taken into account to determine TSM, the use of TSM for risk reduction must be considered as a two-dimensional problem. For instance, does an overall TSM of 5 seconds with no unplanned delay carry the same risk as a minimum DTSM of 5 seconds including 5 seconds of unplanned delay leading to an ITSM of 0 seconds? How about a minimum DTSM of 5 seconds including 2.5 seconds of unplanned delay with an ITSM of 2.5 seconds? Using the DTSM method, each of these have the same overall TSM of 5 seconds, but are they equally risky? The answer to this question seems to rest upon the likelihood of each type of error. Is the pilot more likely to delay past the planned delay time or is he more likely to delay at the worst-case vector?

Thanks to the nature of these maneuvers, the pilot is more likely to delay at the expected recovery start point because this is the automatic result if the recovery is inadvertently delayed. Except for the simplest recoveries, the worst-case vector is passed dynamically and the pilot has little awareness that it has happened; he is much less likely to delay there.

The simplest solution is to use the TSM in the risk reduction and assessment criteria without regard to how much of it came from the unplanned delay. Five seconds of error is five seconds of error, no matter the source. The requirements associated with any particular TSM should prevent a significant exceedance, especially since these requirements are designed in part to ensure that the pilot does not delay significantly beyond the intended recovery condition.

There might be other solutions as well; for a split-s maneuver consider simplifying the maneuver by maintaining the initial N_z all the way to recovery instead of stopping the maneuver in a dive and using a standard nose-low recovery. This may result in more altitude loss, but the altitude loss will be much more predictable as the maneuver is much less subject to error. Sometimes the simplest solution will give the safest result in spite of decreasing the TSM. (Keep in mind that the altitude loss might be increased, making the maneuver less efficient; these are risk management decisions the test team must consider.) It is also very possible that the planned procedure isn't as necessary as tradition would imply; perhaps it is possible to get the time at an elevated N_z using a wings-level pull from a dive instead of using a split-s maneuver. If it is, the overall TSM may be much more favorable.

The most important lesson that DTSM teaches us is that any maneuver that finishes with the dive angle

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[35] There are clearly cases where this is not true, such as a wings-level 0-g push.

increasing carries additional CFIT risk. If the test point can be achieved using a procedure that is completed with the dive angle steady or decreasing, that procedure should be favored. If the procedure must be completed with the dive angle increasing, a sensible amount of delay should be added to the end of the procedure and the effect of additional delay past that point must be considered in the TSM calculation. Delayed TSM is an option for taking that unplanned delay into account in determining TSM.

THE BASICS OF TSM EMPLOYMENT

Time Safety Margin captures the residual CFIT risk of a diving maneuver in a single numerical value that approximates the minimum amount of time available to recognize errors. Time Safety Margin is always an estimate, but the quality of that estimate is a function of the quality of the maneuver planning; reducing the uncertainty of a low TSM can involve dozens of factors and many hours of effort, practice, and buildup. Time Safety Margin should be part of the entire dive planning process, not just a value calculated after the planning is complete. When TSM approaches human reaction time, minimization of uncertainty becomes a life-or-death task.

Test Point Planning for TSM:

If TSM is the CFIT-prevention criteria by which your planning will be judged, it should influence your planning from the very start. If the objective might require a TSM of less than 8 seconds, you will probably need to iterate your TSM planning until your plan meets the requirements for the TSM. Documentation must be thorough enough to ensure correct execution.

Draft a Procedure that Meets the Objective.

Test procedures are designed to gather a specific set of data either through a range of conditions (such as a check descent for performance manual verification) or at a specific condition (such as a weapons separation point). Aircraft performance and handling qualities will heavily influence the procedure required to meet the conditions, so the procedure is often defined entirely by the objective. If you have a physics-based tool to estimate TSM, you should use it to get a rough estimate of the TSM or, if you have some flexibility in the procedure, "rough out" the maneuver, seeking to maximize the TSM while achieving the objective. As with all flight test points, the objective must justify the risk. Time Safety Margin can help quantify the risk and aid the test team and approval authorities in determining if the objective is worth the risk.

Set Terminate and Abort Criteria.

Terminate and/or abort criteria are a vital part of TSM planning. They provide the points in time or space that either call for an immediate recovery when the test point is not going to be successful or when the recovery must be started to preserve the desired safety margins. For unanticipated situations that are developing into a dangerous situation, such as failure to respond to an "Abort!" call, "Knock-it-off!" is commonly used. Edwards AFB instruction 99-103 (2014), *Test Control and Conduct* (reference 6) defines these criteria as follows:

- "Terminate"–ceases flight test execution when continued maneuvering or progress will not achieve desired results.
- "Abort"–alerts flight test crews that planned maneuver limits will be exceeded, and directs aircrew to initiate the planned recovery procedure immediately.
- "Knock-it-off"–alerts flight test crews that a dangerous situation is developing and directs all participating aircrew to cease maneuvering, establish safe flight parameters, deconflict flight paths, and

obtain situational awareness on all flight members.

A properly planned test point will have defined tolerances for critical parameters. These tolerances should be only tight enough to ensure valid data in every corner; too-tight tolerances reduce test efficiency. In general, exceeding a tolerance will call for termination of a test point, but there are instances where a momentary exceedance might be tolerable. Termination criteria are about effectiveness and efficiency—not safety—and are applied with test team judgment.

Abort parameters are typically determined prior to flight—or at the very latest, prior to the execution of the procedure—and are non-negotiable during execution. They should be part of TSM planning if the test maneuver will have less than 8 seconds of TSM. If an abort parameter is exceeded, "Abort!" is called and the aircraft is immediately recovered. Abort parameters are usually achieved after terminate parameters but it is entirely possible for abort parameters to be more restrictive than terminate parameters, especially when successful data collection could result in an unnecessarily hazardous dive. If an abort parameter is inadvertently passed or the pilot fails to respond to an "Abort!" call, a "Knock-it-off!" call is warranted.

With sufficiently high TSM, it is reasonable to use terminate criteria as the trigger to begin the recovery. If TSM is 8 seconds or more, the pilot may be held responsible for preventing CFIT based solely on his routine dive recovery training. In this case, having a separate abort criteria probably isn't necessary; the pilot would be expected to recover upon termination of the test point. If he doesn't, an "Abort!" or "Knock-it-off!" call would be warranted.

Time Safety Margin must be calculated using the worst-case combination of abort criteria (or termination criteria if abort criteria are not used). It is unlikely that all of these criteria will be met at the same instant, so this approach provides additional margin by ensuring that the test team can hit all of their abort and/or terminate criteria at the same time and still have no less than the planned TSM. In general, the worst-case abort will include the maximum allowable dive angle, bank angle, airspeed or Mach, and the minimum allowable altitude. Other abort criteria may be added as necessary, including relevant aircraft system failures, maximum throttle settings if the pilot is modulating the power in a limited range, loss of telemetry, improper chase aircraft positioning, and so on.

Abort conditions are cannot help prevent CFIT if the test team misses an exceedance during execution. As the TSM decreases below 8 seconds, it will be necessary to employ reliable and increasingly extensive techniques to ensure that an "Abort!" call is neither late nor misunderstood. Techniques for this might include technological solutions such as special control room displays and aircraft alerting systems, as well as more traditional methods such as chase aircraft and ground observers. *Limits Based Monitoring of Dynamic Flight Test Maneuvers* (reference 7) is a particularly useful description of a way to use control room displays to reduce the likelihood of exceeding limits.

Plan the Dive Recovery.

If the TSM is going to be less than 8 seconds, the pilot should have a pre-planned recovery procedure. This procedure should be the same regardless of the conditions that initiate it; this will prevent increasing the risk of CFIT by accidentally executing the wrong recovery. Ideally, pilot error will result in less altitude loss, not more.

Inevitable errors during the recovery require the use of safety margins for recovery parameters. For instance, planning to use the maximum allowable N_z during the recovery almost ensures that the pilot will recover at less N_z than planned and lose more altitude than expected. The same goes for planning for the

maximum roll rate, maximum g-onset rate, and the maximum asymmetric N_z (which is particularly unlikely to be achieved).

The closer the recovery parameters are to the aircraft limits and the further they are from the pilot's previous training, the more important practice and buildup become. For the sake of minimizing training and avoiding negative transference, the planned recovery should be very similar to the dive recovery the pilot has trained to use in the aircraft.

Margins need not be added for parameters that are not subject to error or change. For instance, in an over-water test the surface elevation is known so no altitude margin should be necessary; the margin encapsulated in the TSM is enough. If the same test is conducted over land, the surface elevation will change with the location of the dive so the test team must either be very careful about where the maneuver is conducted or, to retain flexibility in scheduling, just use the highest elevation in a specified area.

Do not use altitude margins required by regulations to define the surface elevation for TSM. For instance, consider a test team saddled with a requirement to complete all testing above 2,000 ft AGL: They should plan their maneuver to remain above 2,000 ft AGL, but calculate their TSM using the surface elevation.

As the TSM decreases below about 4 seconds, it might be necessary to plan for such things as the worst expected atmospheric conditions and altimeter lag.

Plan for Expected Recovery Delay.

There will be a measurable time between the decision to end the maneuver and the start of the dive recovery. In some cases, such as an unexpected "ABORT" call from a control room during a maneuver requiring intense pilot concentration, this may be three or more seconds. In other cases, such as a steady dive with a set recovery altitude that the pilot is closely monitoring, this delay may be in tens of milliseconds. Either way, an expected reaction time must be part of the maneuver plan if the addition of the delay will result in a TSM of less that 8 seconds. For instance, if you think your TSM will be 9 seconds but you expect a three second delay between the end of the maneuver and start of the recovery, your actual TSM will be closer to 6 seconds and perhaps even less. It is especially important to plan for expected recovery delay if the dive angle will be increasing at the worst-case abort condition.

Decide How to Handle Unplanned Recovery Delay.

Delayed Time Safety Margin may be employed if your worst-case abort conditions have the dive angle increasing; it is unnecessary otherwise. If you choose not to use DTSM to calculate TSM, it will be very important to ensure that the pilot does not delay past the planned delay time. It might be reasonable to increase the planned delay to add additional conservatism, but the importance of immediate recovery must be emphasized to the test team.

Use TSM to Inform Planning Iterations.

Once the maneuver has been designed, TSM should be calculated in accordance with test organization requirements, normally by using the worst-case parameters. In general, as TSM decreases below 8 seconds, the requirements for computation and model accuracy, buildup procedures, abort decision back-up, pre-flight practice, and pilot cueing will increase. With increased accuracy in the modeling of the aircraft performance and flying qualities, the calculated value of TSM will change. This will either simplify the process by showing that the TSM is better than initially calculated, or it will make things more complex by

adding requirements when the TSM is worse than initially calculated. It is at this point that the test team must decide how to act. Can the requirements be met with a different maneuver? Can the abort criteria be tightened up? Can training be employed to reduce the planned delay time? Can the location of the test point be moved to a place where the terrain is nearer to sea level? Can the dive recovery maneuver be more aggressive?

Consider Training, Buildup, and Currency.

The original AFFTC TSM requirements called for a buildup process prior to attempting any maneuver with less than 8 seconds of TSM (see table 9). If the TSM was less than 4 seconds, simulator rehearsal was also required. These are very reasonable methods to ensure that the pilot and test team are properly prepared and trained for low-TSM maneuvers.

Using TSM for buildup typically starts with flying the maneuver as planned but with at least 8 seconds of TSM. The ideal buildup maneuver would include all support assets, such as a control room and chase aircraft, so the entire team can practice their part in ensuring a safe maneuver. buildup maneuvers are also the best way for a test team to "check their math" by ensuring that their maneuver predictions are correct in the real world. Buildup should start with 8 seconds of TSM and additional buildup runs should be added in proportion to the complexity of the final test point and the calculated minimum TSM.

Simulator practice is a valuable low-cost—and no-risk—buildup step prior to the in-flight buildup process. The test team can evaluate their maneuver and—within the limits of the simulator—judge whether or not their plan will work. Simulator runs to evaluate TSM during the planning process should not be used to meet a build-up requirement unless they occur within a few weeks of the actual flight test; it is important that the actual test team conduct the simulator runs and that they be near enough to the test window to provide currency.

Training and buildup can produce a very well-prepared test team, but that preparation will fade with time. As the TSM decreases below 8 seconds, it will be increasingly important to complete training and buildup just prior to the low-TSM flight test points. Set a limit on how long the test team should go between completion of the training and execution of the test point.

Document the Dive Planning.

The value of a plan is realized in its execution. The test team must understand the assumptions that went into the maneuver planning and must adhere to the plan to preserve the desired TSM. From the required pre-flight training to the completion of the recovery maneuver, a misconception on the part of the test team can severely reduce the TSM and increase the risk of CFIT. Planners should not assume that future members of the test team will be aware of the work put into planning the test point. They must document the plan to guard against their own imperfect recollection and to provide for the education of new team members.

Test Point Execution with TSM:

The first step in executing a safe and effective diving maneuver—especially one with a TSM of less than 8 seconds—is understanding the objective of the maneuver and the procedure, recovery, and planned delays that went into the TSM computation. Adherence to the plan is vital but flight test often presents unexpected challenges so the test team must know when the plan has gone awry and react accordingly.

Prepare for Success.

Weeks, even months, can pass between the completion of test planning and the execution of the plan. Even if the first test points are flown the day after final test plan approval, the last test points—often the most hazardous—may be so delayed that the planning process will become a distant memory.

Dive maneuver planning often entails a concentrated effort. The reasons for important decisions and the assumptions behind them may be forgotten or may have gone with the author upon acceptance of a new job. Ideally the test and safety plan will be complete enough that this will not matter but it is more likely that important information will be left out because it seemed very obvious to the planning team as they concentrated on their work.

The test execution team should take a new—and critical—look at the test and safety plan as the test event approaches. Did the planners miss anything? What doesn't make sense? Is it too conservative or not conservative enough? The level of this effort should inversely correlate with the TSM; as the TSM decreases below about 4 seconds the test team will need to be at the top of their game by having an excellent understanding of the procedure, the recovery, and the plan by which the team will safely execute the entire maneuver.

Complete Required Training and Buildup.

When required, training and buildup must be carefully conducted in accordance with the plan.[36] Your TSM is only as good as your models and your ability to conduct the maneuver; the lower the TSM is, the more important these factors become and you must safely evaluate and practice the maneuver prior to attempting it in conditions where you only have a few seconds of margin.

Fly in Accordance with the Plan.

For an experienced test professional, this is obvious, but the temptation to improvise can be powerful in the midst of the "late-cycle churn" that flight test teams so often find themselves in. A mishap, fatal or not, will create *much* more delay, cost, and effort than preventing the mishap and may even cause the cancellation of an important acquisition program.

ADDITIONAL CONSIDERATIONS FOR TSM EMPLOYMENT

The requirements designed for the initial deployment of TSM provide a good starting point for any organization choosing to use the method, but it is easy to lose some of the fundamentals in the details of a specific set of rules. It is not just a risk assessment tool; it should be used to scope the level of effort a test team puts into planning diving test points.

Test planners and teams must keep in mind that TSM is only designed to prevent CFIT; very comfortable TSMs are completely insufficient should aircraft control be lost through unexpected events such as mid-air collision, structural failure, departure from controlled flight, disorientation, or g-induced loss of consciousness.

TSM and Safety Risk Assessment:

The assumptions and approximations that go into calculating TSM assure that the value of TSM cannot be thought of as an absolute measure of CFIT risk. To build margin against unknowns, TSM is calculated

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[36] There are instances of simulator practice runs unexpectedly ending in a ground collision.

using the worst-case recovery initiation conditions. This "worst-case TSM" is probably significantly less than the TSM for the nominal recovery condition.[37]

Time Safety Margin would be more valuable as a risk assessment tool if it was practical to include a measure of uncertainty. It is natural to assume that 4 seconds of TSM is less safe than 8 seconds of TSM, but this assumption is based on a deeper assumption that the precision of the these values is comparable. A poorly planned 8 second TSM maneuver might entail much more CFIT risk than a tightly planned and practiced 4 second TSM maneuver.

To examine the expectations of TSM accuracy in relation to risk assessment, we will look at the USAF Test Center instructions regarding test safety review, AFTC Instruction 91-202 (2016), *AFTC Test Safety Review Policy* (reference 8). According to this document, if the probability of ground impact (a catastrophic mishap) is 10^{-3} or greater, an assessment of "high risk" is warranted. A "medium risk" assessment is warranted until the probability decreases below 10^{-6}. With a few simple assumptions we can use these probabilities and the worst-case TSM thresholds in table 9 to roughly estimate the corresponding nominal-case TSMs. Let's assume that the probability of exceeding the expected worst-case condition is 2 percent; that one out of every fifty attempts will result in an actual TSM of less than the worst-case TSM. Let's also assume that the distribution of actual maneuver TSMs around the nominal-case TSM is a normal (Gaussian) distribution.[38] With these assumptions, the worst-case TSM is about two standard deviations less than the nominal-case TSM. Using the cumulative normal distribution function, we can estimate that a nominal TSM of 6.9 seconds produces a 10^{-6} chance of ground impact when the worst-case TSM is 4.0 seconds. For the high risk worst-case TSM threshold of 2.5 seconds and a 10^{-3} chance of ground impact, the nominal TSM is 7.1 seconds. Paradoxically, this implies that the presumed risk assessment allows for less accurate planning than the lower, "riskier" TSM. The presumed risk assessments did not originate in statistical analysis; they were largely based on the risk assessment framework provided by ART (reference 3) and the instincts of the authors and reviewers.

If we push our statistical assumptions to the breaking point, we can determine that if our planning and training is good enough to assure that 98 percent of our actual TSMs will be within 0.5 seconds of the nominal TSM, the nominal-case TSM for the medium risk threshold of a 10^{-6} chance if ground impact is about 1.2 seconds, with a worst-case TSM of 0.7 seconds. While mathematically correct, this shows the limitations of our assumptions. A test team that tried to make this argument would be castigated for their failure to account for the many unknowns that TSM cannot capture. On the other hand, if a test team must conduct a test point that results in a worst-case TSM of 3.0 seconds yet, through excellent planning and buildup, can show that their nominal-case TSM of 4.0 seconds (presumed medium risk) is about two standard deviations from their worst-case TSM, they should be able to argue that their actual risk is quite low. (If you assume a normal distribution with a mean of 4.0 seconds of TSM and a standard deviation of 0.5 seconds, the chance of ground impact (corresponding to TSM < 0.0 sec will be on the order of 10^{-15}. This should not be the basis for a "low risk" assessment, but it is a start.)

It is important to understand that the "presumed risk assessment" levels in table 9 were *not* determined using any kind of statistical analysis. They were based upon human reaction time and the judgment of the author and reviewers. The TSM requirements specified in table 9 are primarily intended to reduce variability in diving maneuvers as the room for error diminishes, not to aid risk assessment. Additional planning can

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[37] "Nominal recovery condition" is a recovery that starts exactly as expected and is recovered exactly as planned; the perfectly-flown test point.

[38] There is no reason to believe that the probability distribution of TSM is Gaussian, but we can use this assumption to approximate the roughly bell-shaped distribution of realized TSMs around the nominal maneuver.

reduce the risk of ground impact even as the TSM is diminishing; presumed risk assessments like those of table 9 should not be treated as the final word.

TSM with Additional Altitude Margins:

Time Safety Margin is designed to make altitude margins unnecessary measures of safety. Altitude margins are only applicable within a limited—and often unacknowledged or misunderstood—range of conditions. *The TSM should be calculated as a margin for CFIT, not for flight through a minimum altitude.* If operating procedures do not allow a maneuver to go below a certain AGL altitude, the best practice is to plan the maneuver to remain above that altitude but calculate TSM using the surface elevation. Time Safety Margin is the margin from ground impact, not from a violation of regulations.

The most obvious example of this type of rule is a specified minimum altitude for certain types of test points. Let's imagine an organization that has the following directive in place: "No test points shall be conducted below 1,000 feet AGL." A rule like this can create a wide range of problems. On one end, 1,000 feet is worth about 0.5 seconds of TSM in a Mach 2 vertical dive so the minimum altitude produces an insignificant amount of margin. On the other end, the minimum altitude ensures about 20 seconds of TSM for a 10-degree dive at 150 KTAS, producing inefficiency with excessive margin. Somewhere in the middle, the restriction makes sense, but that somewhere is highly dependent on airspeed, recovery technique, dive angle, and so on. Regardless of regulatory requirements, test teams should use TSM to understand their safety margins relative to CFIT.[39]

Using TSM to Scope Planning and Buildup Costs:

Time Safety Margin is more than a risk assessment tool; it may be used to help scope the amount of cost and effort put into test planning. The amount of effort put into fully understanding the maneuver and the aircraft, and into training the pilot and test team, should increase exponentially as TSM is reduced. At one end of the TSM spectrum—at least 8 seconds of TSM—any qualified pilot might be trusted to plan and execute the maneuver, but at the other end—*no* TSM—it is hard to imagine any amount of planning that could be considered "sufficient." The guidance provided for the original publication of TSM regulations in the USAF is a good start but other organizations might find better—or more applicable—ways to use TSM in their dive planning.[40]

Avoiding Excessive Planning Cost when TSM is Very High:

Time Safety Margin provides a very convenient and effective method for identifying, understanding, and controlling risk during diving maneuvers but attempting to accurately determine TSM can produce severe over-planning for dives with a high TSM. Consider a 0.8 MN, 10-degree dive at 45,000 feet AGL; the TSM for this dive is about 5 *minutes*. (Using 800 feet per second and 3,000 ft terrain elevation, TSM is approximately $42,000/(800 \sin 10) = 302$ seconds; even this much planning is arguably overkill.) Clearly there are a lot of dives that produce such obviously high TSMs that almost any effort spent calculating TSM is wasted.

The figures in appendix A provide one way around spending too much time on TSM when TSM is clearly not a factor. These figures show the AGL altitude that corresponds to 8 seconds of TSM for a variety

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[39] TSM has been successfully used to ease the process of obtaining a waiver for onerous or inapplicable regulatory requirements.

[40] When AFMC adopted TSM, the published guidance for "Automatic Recovery TSM" (1.5>TSM≥0 seconds) was changed to "Not Authorized." This had the effect of elevating the approval authority for this type of test by requiring a testing agency to seek a waiver if a TSM of less than 1.5 seconds was required for their program.

of bank angles and recovery load factors, from Mach 0.15 through Mach 2. If the planned test procedure and recovery clearly lie within the assumptions for these charts and the planned minimum recovery start altitude is less than that shown for 8 seconds of TSM, then TSM planning may be considered complete.[41] These figures are divided into three sets; wings-level dives, 90-degree bank dives, and inverted dives.

Figure 23 is provided here as an example. The platform-independent predictions on this figure assume a constant Mach number for the entire maneuver (Mach is found on the horizontal axis), a wings level steady-state dive prior to the recovery start altitude shown on the vertical axis, and no unplanned delay. Mach and recovery start altitude are given on logarithmic scales. It takes 3 seconds to achieve 6 g from the steady-state N_z for each dive angle. Reference lines for seven dive angles are used to depict the altitude/Mach number combinations that result in 8 seconds of TSM.

For example, assume a steady wings-level dive procedure that has a minimum altitude of 10,000 feet AGL, a maximum Mach of 0.9, and a maximum dive angle of 30 degrees. Find the point on the chart at the intersection of 0.9 MN and 10,000 feet. Note that this point is well above the 8 second TSM line for a 30-degree dive. This means that the TSM is greater than 8 seconds provided the conditions and assumptions are met. If the recovery is started at 5,000 feet in an otherwise similar dive, the chart shows that a 30-degree dive would be too steep for 8 seconds of TSM while a 20-degree dive would provide at least 8 seconds of TSM.

Maneuvers in Low Visibility and at Night:

Time Safety Margin is only defined by the planned maneuver. Strictly speaking, so long as the pilot has the tools and skills necessary to fly the procedure and recovery, the TSM will not be changed by the amount of ambient lighting or the pilot's view of the ground. (Although visual cues can provide a low-resolution and better-than-nothing backup to missing required recovery initiation parameters, TSM must not be based in any way upon the pilot using visual cues like "ground rush" to determine when recovery is required.)

The risks presented by low visibility and night conditions do not have anything to do with the geometry of the procedure or the dive recovery; the risks are almost entirely the result of the potential for pilot spatial disorientation. The pilot might have all the information he needs to accomplish a safe recovery, but without the help of a visible horizon he is much more likely to subconsciously misinterpret somatosensory and vestibular cues—to experience spatial disorientation. A disoriented pilot is much less likely to correctly interpret the instruments and fly the recovery as designed; in fact, a disoriented pilot is much more likely to make the situation much worse. A disoriented pilot may be no more capable of recovering correctly than an unconscious pilot.

The bulk of the effort put into planning night or low-visibility diving maneuvers should be spent on preventing, identifying, and recovering from spatial disorientation. The less likely the pilot is to become disoriented, the more reasonable it is to use TSM thresholds designed for clear daytime skies. Maneuvers must be designed to minimize the chance of disorientation and to provide a backup plan that does not rely on the pilot regaining orientation.

When designing for a successful night or low-visibility dive and dive recovery, avoid high N_z, high roll rate, and high roll acceleration. Inverted flight is particularly problematic but any roll angle higher than about 30 degrees will add risk. Technology like night vision goggles can help, of course, but the pilot must

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[41] This argument follows from the idea that 8 seconds of TSM is typical of the minimum margin routinely used in basic operational flying by qualified pilots. With this much margin, you should be able to rely upon operationally-developed judgment for dive recovery safety.
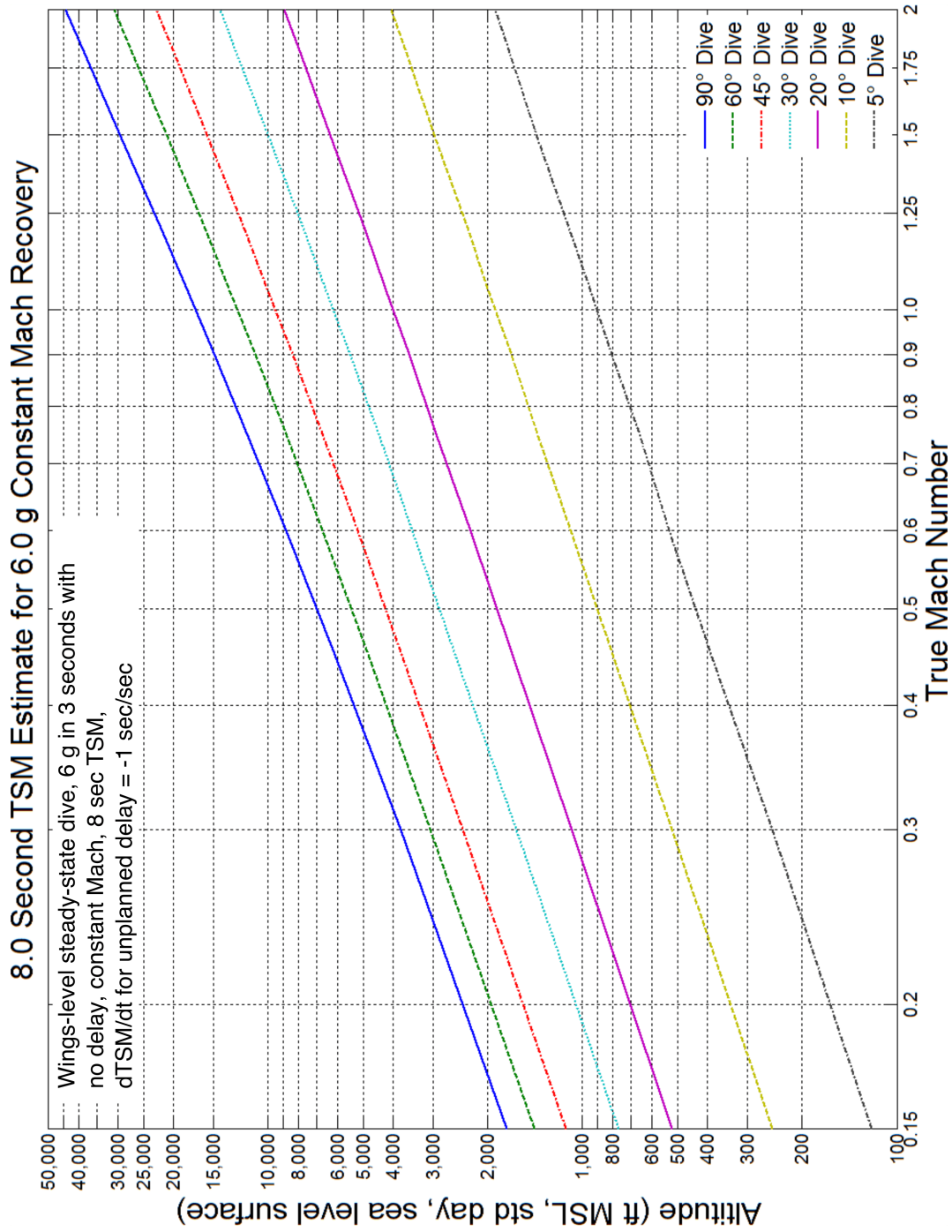
Figure 23 Eight Second TSM Estimates for a 6-g Recovery from a Wings-Level Dive

have the correct training in their use. If the aircraft has a pilot-activated automatic recovery system, planning to use that system instead of a pilot-flown recovery could be beneficial. If the cockpit has more than one set of controls, a safety pilot may be assigned with the primary role of maintaining attitude awareness and recovering as required. A control room can help with maneuver setup and recovery calls, but probably cannot help much with the actual recovery.

Time Safety Margin is perfectly valid for night and low-visibility testing, but the minimum TSM for the maneuver must be adjusted upward as the probability of pilot spatial disorientation increases. It is probably better to concentrate on preventing disorientation, not on trying to figure out how much TSM is required for a disoriented pilot; if you think the pilot may become incapacitated by disorientation, you have a much bigger problem than TSM.

Reality Check—There is no "Universal" Solution for Dive Planning:

It is impossible to perfectly calculate TSM. Time Safety Margin is a tool to help plan diving maneuvers, it is not a deterministic means of characterizing dive maneuver risk; it is not a "law of nature." TSM should be based on the worst-case abort scenario combined with a reasonable, reliable, and conservative recovery profile so that there is sufficient margin for the many ways that the actual maneuver will differ from the plan. The uncertainty inherent in any TSM calculation means that TSM time range requirements should not be seen as definitive goals, but as thresholds to rationally drive planning effort and risk mitigation. Time Safety Margin should be used as a tool to improve the process of planning diving maneuvers, not as a means of encouraging arbitrary decision-making.

TSM EXAMPLES

These examples will be presented primarily with the use of TSM Awareness Tool estimations.[42] These examples are intended to help the reader better understand TSM in general and their dive recovery problem in particular, not to provide a recipe for every class of recovery.

WINGS-LEVEL DIVES

<u>Using a Flight Manual to Estimate TSM:</u>

If the TSM will be high enough (the original AFFTC instructions drew the line at 8 seconds for "routine" TSM), it is reasonable to determine TSM using available data, such as flight manual dive recovery tables. For a wings-level dive, a simple back-of-an-envelope calculation should produce results that are accurate enough to ensure the TSM is significantly greater than 8 seconds.

Flight manual dive recovery charts are typically designed to give the altitude lost during a dive recovery using the conditions at the initiation of the recovery including airspeed and/or Mach, initial altitude, dive angle, and recovery load factor (N_z in units of g). It is a simple matter to calculate how long it would take to get from the planned recovery initiation altitude to the AGL altitude equal to the expected altitude lost in the dive.

$$\text{TSM} \approx \frac{\text{Planned Recovery Initiation Altitude} - \text{Minimum Recovery Initiation Altitude}}{\text{Average True Airspeed} \times \sin{(\text{Dive Angle})}}$$

Keep in mind that the method chosen to calculate TSM will affect the uncertainty of that calculation. If the TSM calculation carries, say, a 1 second uncertainty, it is more than accurate enough for a 20 second TSM calculation but completely inadequate for a 2 second TSM. The original AFFTC TSM requirements reflect this in the "planning fidelity" requirements for different amounts of TSM (table 9). It is extremely important to employ sufficient planning for a hazardous dive, but it is also important for help control cost and schedule risk by not employing excessive fidelity for dives that have ample TSM.

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[42] The "TSM Awareness Tool" is a Matlab graphical user interface designed to provide a 3D physics-based estimation of TSM. The user manual is located in appendix C.

Weapons Delivery (Figure 24):

This scenario is for a 30-degree diving delivery at 450 KCAS, releasing at 4,000 ft AGL over a sea-level target. Operational requirements call for terminating the delivery procedure and recovering if the airspeed is 50 KCAS fast, if the dive is more than 5-degrees steep, or if the minimum release altitude of 3,700 ft AGL is passed. As is routine with a weapons delivery, the recovery is delayed for one second after release. With this information, TSM is based on the worst-case recovery conditions of a 35-degree dive at 500 KCAS with the release occurring at the minimum altitude of 3,700 ft. The resulting TSM is 3.1 seconds. This TSM seems low, but it is typical for this type of diving weapons delivery; it reflects the amount of training and planning these maneuvers require of operational pilots.

If the exact planned parameters are used to calculate TSM the result is almost twice as long, giving the impression that the delivery procedure is much less hazardous than it actually is or—more precisely—could be when correctly flown within maneuver limitations. This is a good illustration of why you must always use the worst-case recovery parameters and abide by criteria that require procedure termination if *any* of these parameters are exceeded.
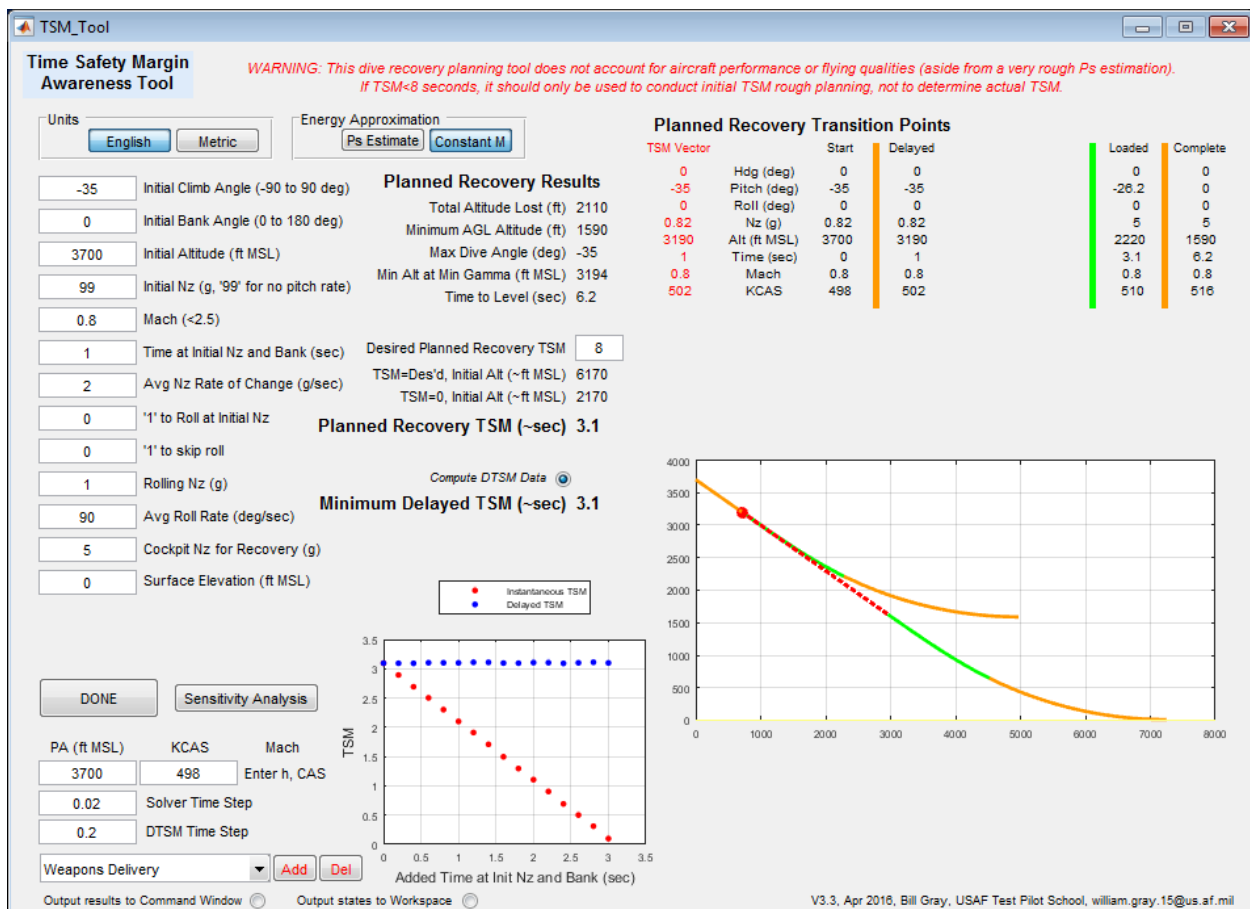
Figure 24 Example: Diving Weapons Delivery

Ground Proximity Warning Test (Figure 25):

One of the most valuable uses of the TSM methodology is to eliminate unnecessary buildup. Pilots tend to think of altitude lost or minimum altitude as the best metric for ensuring safety during dive recoveries, but we have seen that this intuition is false. One thousand feet of buffer may be plenty for one maneuver but completely meaningless for another. This example depicts what would appear to be a steep dive for a large aircraft on a fairly fast final. The initial conditions are a 10-degree dive at 145 KCAS and 500 feet AGL. One second of planned delay is added for pilot response time and just 1.5 g is planned for recovery. For this situation, TSM is a relatively generous 8.7 seconds.

Of course, this assumes that everything goes exactly as planned. If you assume that the dive angle might be as much as 2 degrees too steep, the speed 10 KCAS fast, and the delay time for recovery as long as 2 seconds, you will need to add a few hundred feet to the planned recovery altitude to ensure a TSM of at least 8 seconds.
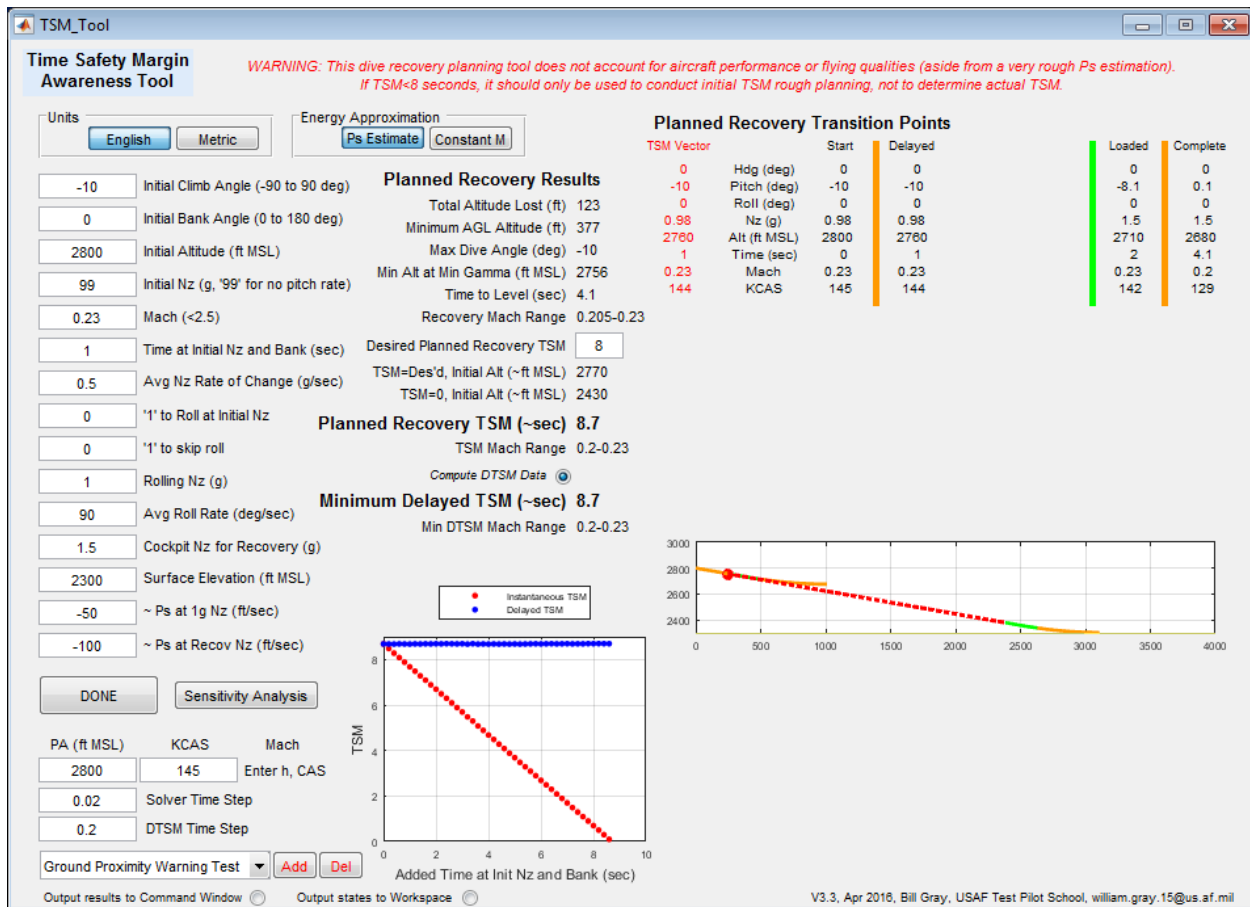
Figure 25 Example: Low Speed GPWS Test

USAF Test Pilot School Shuttle Approach Simulation (Figure 26):

At the start of the Space Shuttle program, astronauts trained to fly the Shuttle final approach and flare using a T-38 Talon trainer aircraft. This profile was adopted by the USAF Test Pilot School (TPS) to support the aircraft performance curriculum and remains an event that all students fly. The Space Shuttle final approach was very steep and very fast, but the T-38 can fly steeper and faster when light-weight. There are limitations on the dive angle and airspeed (30 degrees and 300 KCAS, respectively) and when the aircraft is flown at these limitations and the flare is started at the minimum—and normal—flare altitude of 1,000 ft AGL, the TSM is only 2 seconds. It is very difficult to get this steep without exceeding the airspeed limit of 300 KCAS so this scenario is highly unlikely. Under nominal approach conditions at the lowest allowable weight the TSM is 4.4 seconds (corresponding to a 24-degree dive at 275 KCAS).

All landings involve a descent close to the ground; the margin between the start of a normal flare and the point at which a hard landing is assured is typically not much more than a few seconds. This is why pilots spend a lot of time training to land their aircraft and practice landings regularly. Very short TSMs can be perfectly reasonable, but only at the cost of training and practice. The USAF TPS shuttle approach profile requires a special pilot checkout program and must be practiced by each qualified pilot at least once every six months.
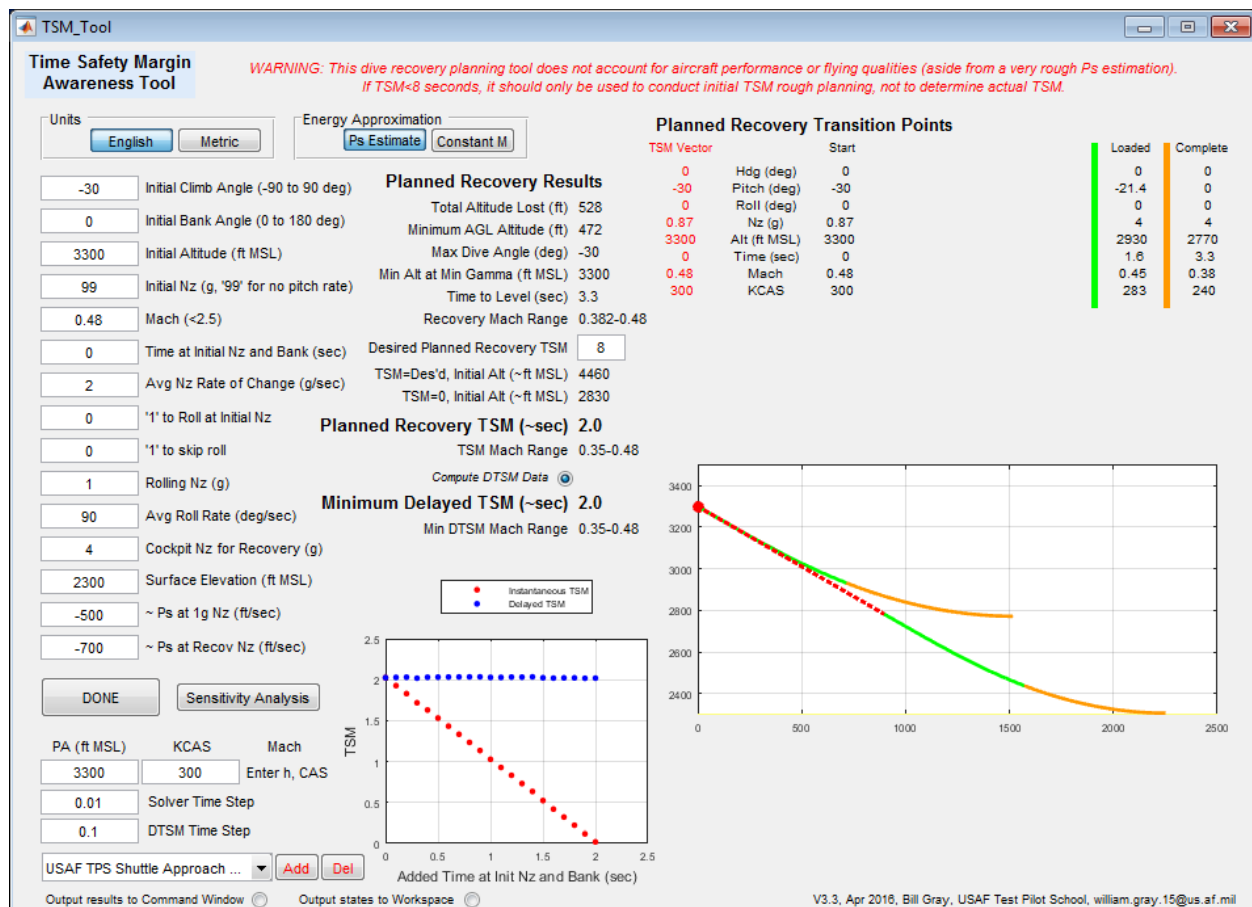
Figure 26 Example: USAF Test Pilot School "Shuttle Approach"

INVERTED OR TURNING DIVES

High Mach Split-S, High Thrust (Figure 27):

A split-s procedure offers additional dive recovery risks. During the procedure the dive angle is rapidly increasing so any unplanned delay past the intended maximum dive angle rapidly decreases the ITSM. This example gives a comfortable 7.1 seconds of ITSM when recovering from the planned maximum dive angle of -30 degrees. But each second of unplanned delay at the initial N_z decreases the ITSM by more than 3 seconds. It only takes about 2.2 seconds of unplanned delay for the ITSM to go to nil; therefore the DTSM is a very short 2.2 seconds. Put more directly, if the pilot continues pulling for a little more than 2 seconds past the planned maximum dive angle, executing the planned recovery will result in ground impact.

One of the reasons that the DTSM for this maneuver is so low is that it is built around the assumption that the thrust is set such that the airspeed would remain roughly constant in a level turn at the recovery N_z. As the aircraft is unloaded and rolled during the dive, the Mach number rapidly builds to a maximum of 1.3 MN from the initial 0.9 MN. This increases the turn radius and the altitude lost during the recovery. It is also not very realistic, as the very simple energy approximation algorithm does not take into account wave drag. (On the other hand, it is conservative; the TSM using actual aircraft performance would probably be significantly higher.)

TSM_Tool

Time Safety Margin Awareness Tool

WARNING: This dive recovery planning tool does not account for aircraft performance or flying qualities (aside from a very rough Ps estimation). If TSM<8 seconds, it should only be used to conduct initial TSM rough planning, not to determine actual TSM.

Units: English | Metric

Energy Approximation: Ps Estimate | Constant M

Planned Recovery Transition Points

	TSM Vector	Start		Unloaded	Rolled	Loaded	Complete
Hdg (deg)	3	0		0	3	3	3
Pitch (deg)	-56.7	-30		-54.7	-56.4	-49.8	0.1
Roll (deg)	56	180		180	0	0	0
Nz (g)	1	9		1	1	6	6
Alt (ft MSL)	21430	25000		22840	20780	19000	14680
Time (sec)	4	0		2.7	4.7	6.3	14
Mach	1.22	1.1		1.17	1.25	1.3	1.41
KCAS	579	480		537	599	649	761

Input	Label
-30	Initial Climb Angle (-90 to 90 deg)
180	Initial Bank Angle (0 to 180 deg)
25000	Initial Altitude (ft MSL)
9	Initial Nz (g, '99' for no pitch rate)
1.1	Mach (<2.5)
0	Time at Initial Nz and Bank (sec)
3	Avg Nz Rate of Change (g/sec)
0	'1' to Roll at Initial Nz
0	'1' to skip roll
1	Rolling Nz (g)
90	Avg Roll Rate (deg/sec)
6	Cockpit Nz for Recovery (g)
3000	Surface Elevation (ft MSL)
500	~ Ps at 1g Nz (ft/sec)
100	~ Ps at Recov Nz (ft/sec)

DONE | Sensitivity Analysis

Planned Recovery Results

Result	Value
Total Altitude Lost (ft)	10319
Minimum AGL Altitude (ft)	11681
Max Dive Angle (deg)	-57
Min Alt at Min Gamma (ft MSL)	21434
Time to Level (sec)	14
Recovery Mach Range	1.1-1.41
Desired Planned Recovery TSM	8
TSM=Des'd, Initial Alt (~ft MSL)	26680
TSM=0, Initial Alt (~ft MSL)	13650

Planned Recovery TSM (~sec) 7.1
TSM Mach Range 1.1-1.69

Compute DTSM Data ⦿

Minimum Delayed TSM (~sec) 2.2
Min DTSM Mach Range 1.1-1.63

Legend: Instantaneous TSM | Delayed TSM

PA (ft MSL)	KCAS	Mach
25000	480	Enter h, CAS
0.02		Solver Time Step
0.2		DTSM Time Step

High Mach Split-S, High Thrust ▼ | Add | Del

Added Time at Init Nz and Bank (sec)

Output results to Command Window ○   Output states to Workspace ○

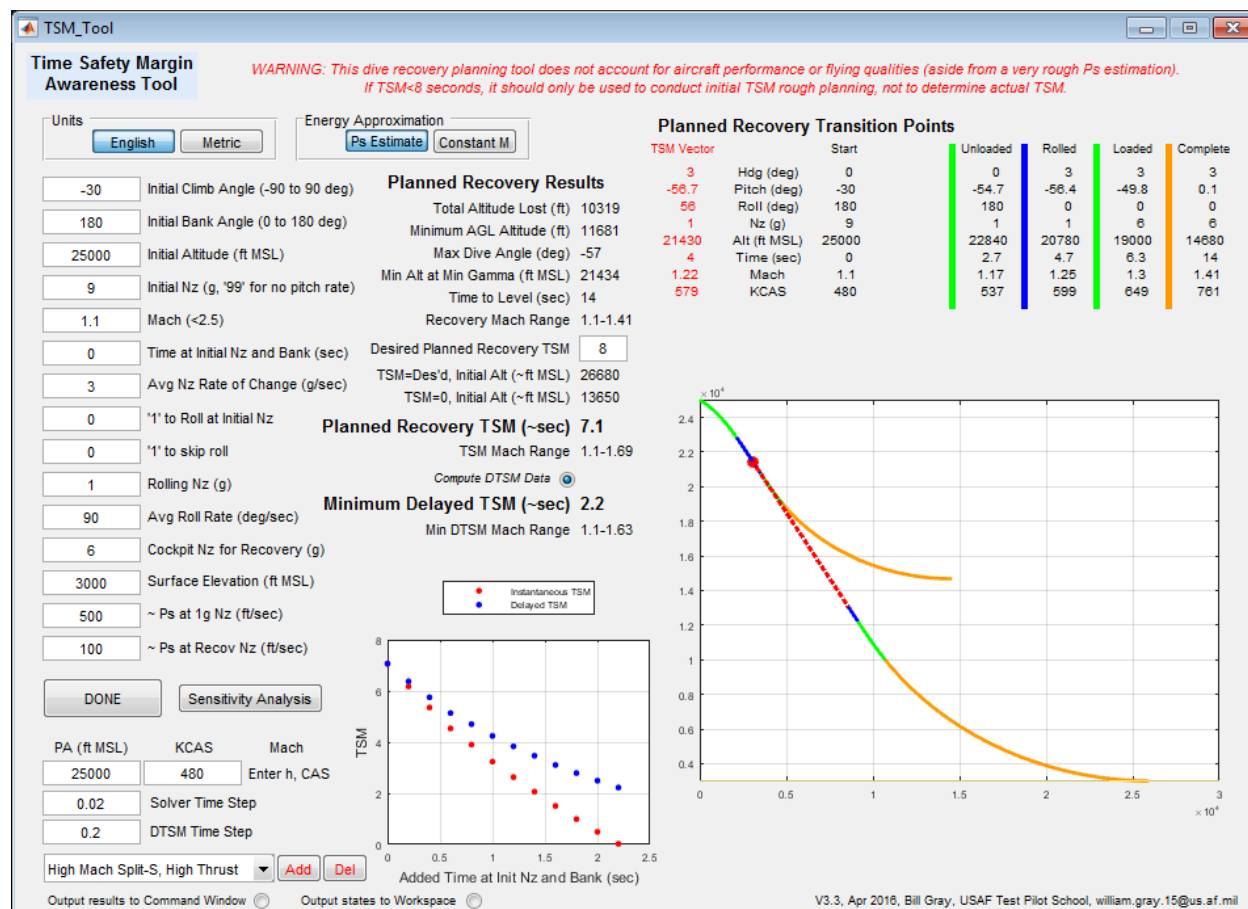V3.3, Apr 2016, Bill Gray, USAF Test Pilot School, william.gray.15@us.af.mil

Figure 27 Example: Split-S Procedure with High Thrust

High Mach Split-S, Low Thrust (Figure 28):

If we run the same scenario as the high-thrust split-s procedure, but with the energy approximation set to approximate a minimum power setting in a fighter aircraft, we get significantly improved results from the same initial conditions. Although the ITSM decreases about 8 seconds, the DTSM only decreases to 4.9 seconds and there is no unplanned delay that results in an unrecoverable condition (ITSM<0 seconds).

The DTSM graph has some interesting discontinuities. These correspond to how the unplanned delay affects the recovery algorithm. In the first section, up to about 2 seconds of unplanned delay, the dive recovery is as expected; the aircraft N_z is reduced then it is rolled to wings level and loaded up to the recovery N_z. The last section corresponds to where the planned delay causes the aircraft to be pulled past the vertical. Once this happens, the aircraft is just unloaded directly to the recovery N_z without producing the altitude loss caused by unloading to the low rolling N_z. The middle section results from the aircraft passing the nadir while being unloaded to the rolling N_z then, after unloading for the roll and finding that there is no need to roll, the pilot immediately pulls to the recovery N_z.
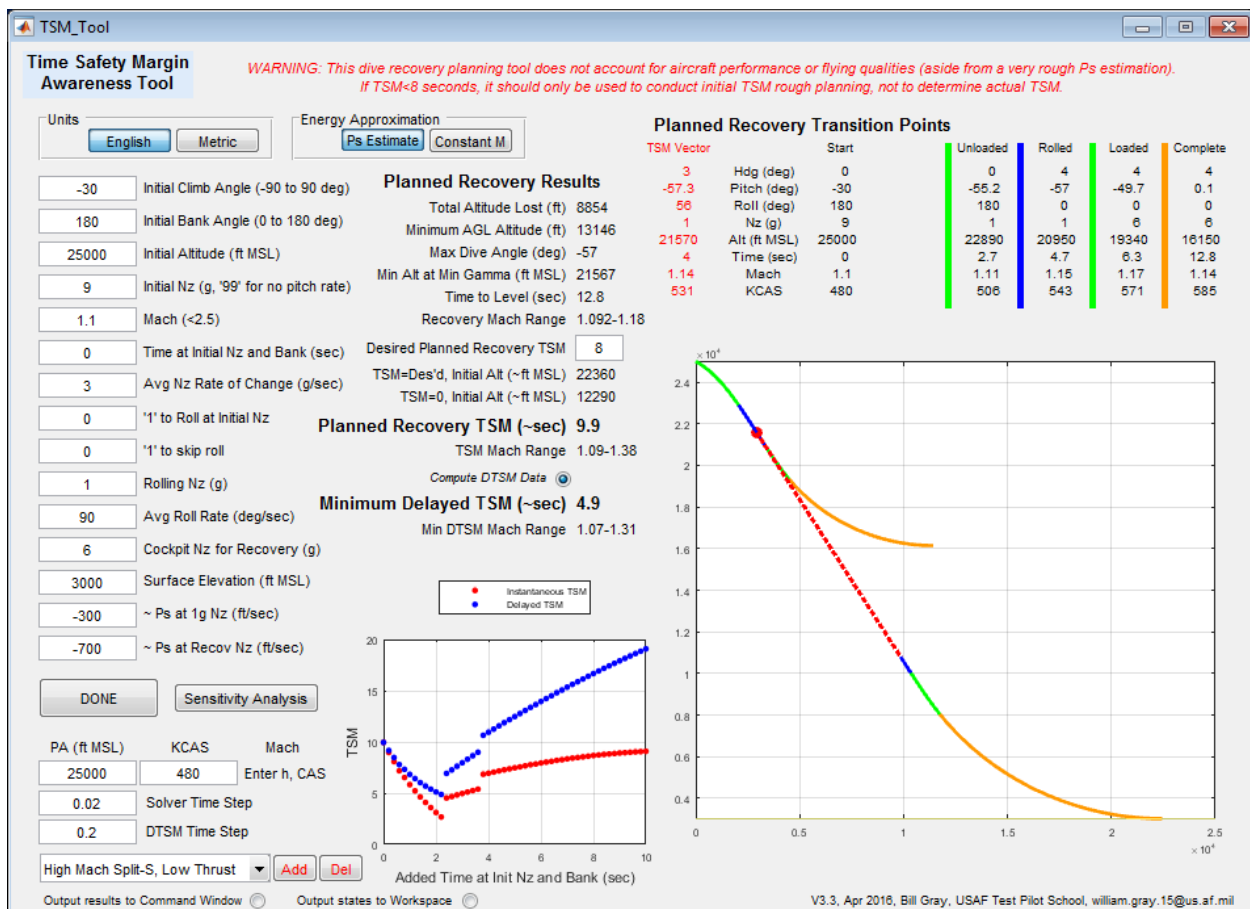
Figure 28 Example: Split-S Procedure with Low Thrust

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High Mach Split-S, High Thrust Pulled-Through (Figure 29):

Sometimes a standard dive recovery is a bad idea. This example shows what happens when we take the very worrisome "Split-S Procedure, High Thrust" case and just set it up to continue the on-conditions pull of 9 g.[43] By just continuing the pull until level flight the DTSM is now a very reasonable 5.5 seconds.

There are other factors to consider for this particular maneuver, though. Most importantly, this has the pilot at 9 g for about 12 seconds so you have to account for that in your planning. If the pilot loses consciousness during a split-s procedure, the TSM probably doesn't matter!
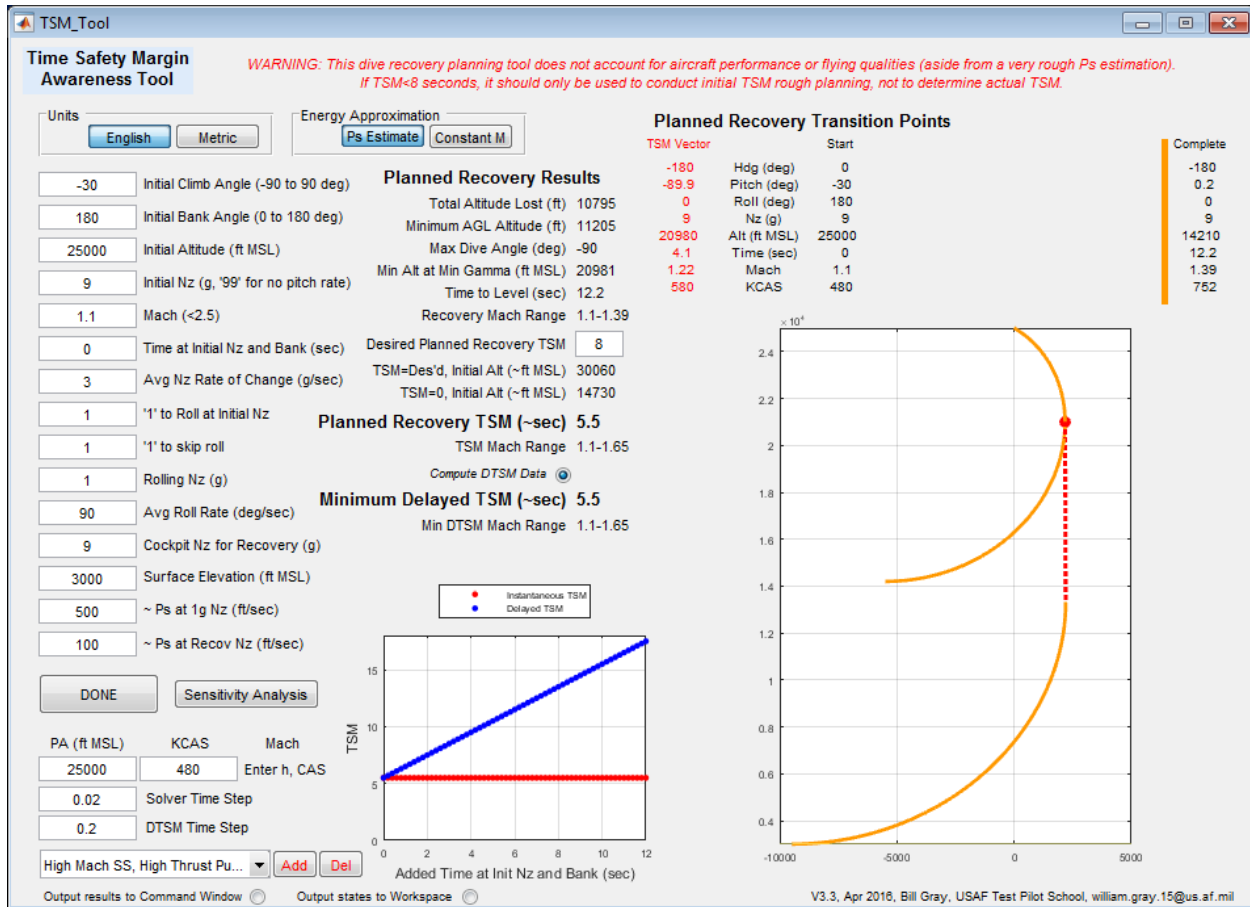
Figure 29 Example: Split-S Procedure, Pulled Through with High Thrust

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[43] In GUI, this is done by changing both "'1' to skip unload to rolling Nz" and "'1' to skip roll" to "1," then changing the recovery N_z to match the initial N_z.

Wind-Up Turn (Figure 30):

This scenario illustrates a wind-up turn. It assumes that the minimum altitude (bottom of the data band) is 8,000 ft MSL, 5,000 feet above the surface elevation of 3,000 ft MSL. The maximum airspeed is 250 KCAS, the maximum allowable dive angle is 45 degrees, and the maximum bank angle is 90 degrees. This maneuver results in an ample ITSM of 9.6 seconds. The DTSM is also 9.6 seconds but, thanks to the dynamics of the maneuver, the ITSM actually improves if the pilot delays past the expected delay of one second.

You can check the sensitivity of DTSM and ITSM to changes in the entry parameters by making small changes in each parameter—only one parameter at a time—and running the simulation to see how it affects the TSM. For instance, in this scenario an increase of 5 degrees to the initial dive angle results in a one second reduction in TSM. Adding 10 degrees of bank has about the same effect. It would seem that a small decrease in recovery N_z would have about the same effect, but N_z is not a critical part of this recovery; the recovery N_z must be reduced from 5 g to about 2.4 g to have the same effect on TSM as the 10-degree bank or 5-degree dive changes. Increasing the recovery N_z to 9 g only improves the TSM by about a tenth of a second; the recovery is complete when the aircraft hits about 7 g so it never reaches 9 g.
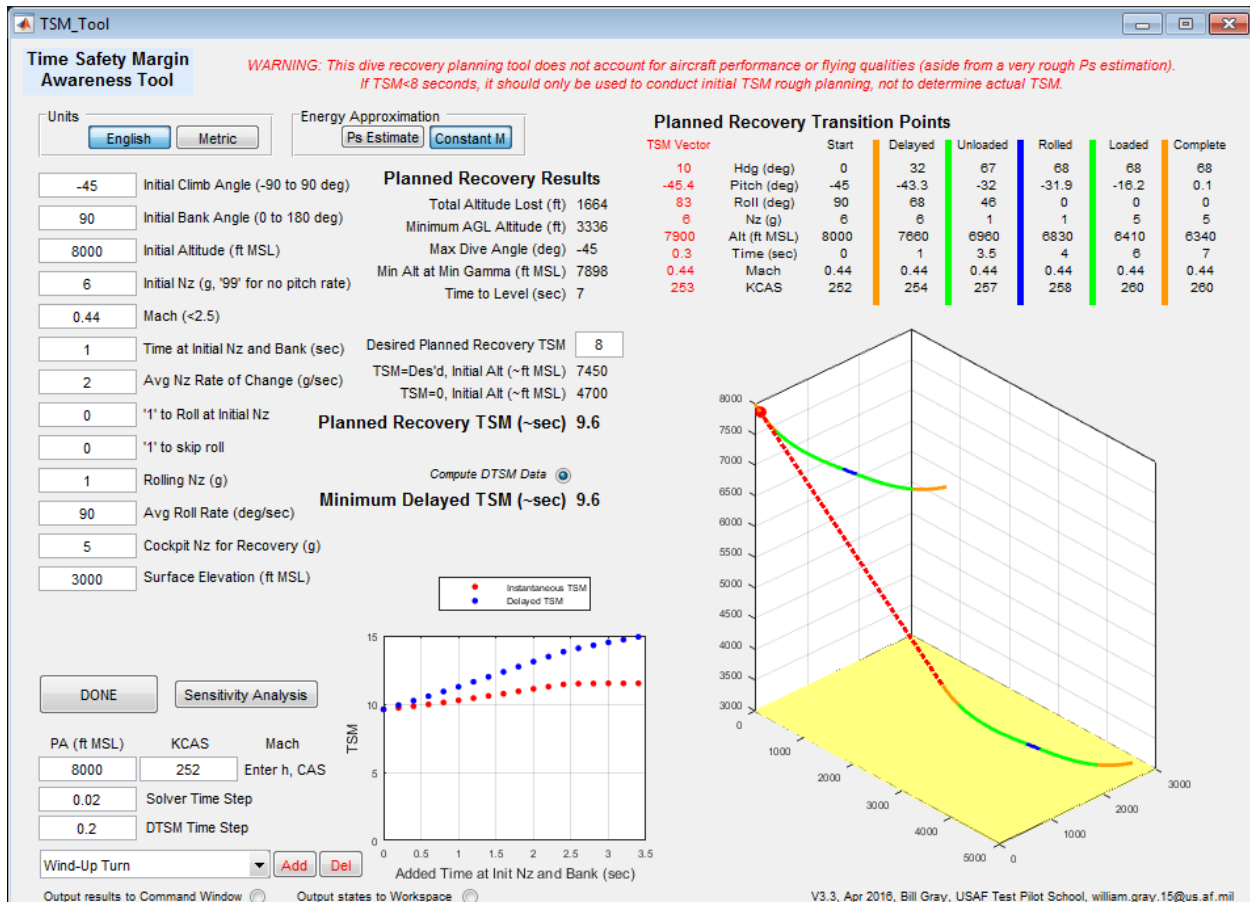
Figure 30 Example: Wind-Up Turn

Inverted, Negative Cockpit N_z (Figure 31):

Sometimes sustained negative N_z flight is required. Sometimes it has to be at low altitude. The TSM considerations can be very interesting. Figure 31 depicts a profile that assumes a minimum altitude of 3,000 ft AGL, maximum dive angle of 10 degrees, and a minimum N_z of -0.5 g. At these conditions, the dive angle will be increasing slightly and the pilot must return to 1 g to roll. The former means that the DTSM is less than the ITSM with no unplanned delay (the pilot may persist in the initial conditions for 4.1 seconds before recovery as planned becomes doubtful) and the latter means that the pilot must increase the dive angle by pulling to 1 g prior to rolling from inverted. For the no-unplanned-delay case, this means that the maximum dive angle is 16 degrees. At any rate, the overall minimum DTSM—and overall TSM– for this maneuver is 4.1 seconds.

This example illustrates the importance of having and abiding by relevant worst-case conditions. If the recovery is not initiated for a steeper-than-10-degree dive angle then the reasonable TSM is no longer valid and recovery could be impossible in just a few seconds. Pilot technique will also be important here; if the pilot has practiced inverted level flight this should be a very easy test point to achieve. If not, the test team better be ready to call "Knock-it-off!"
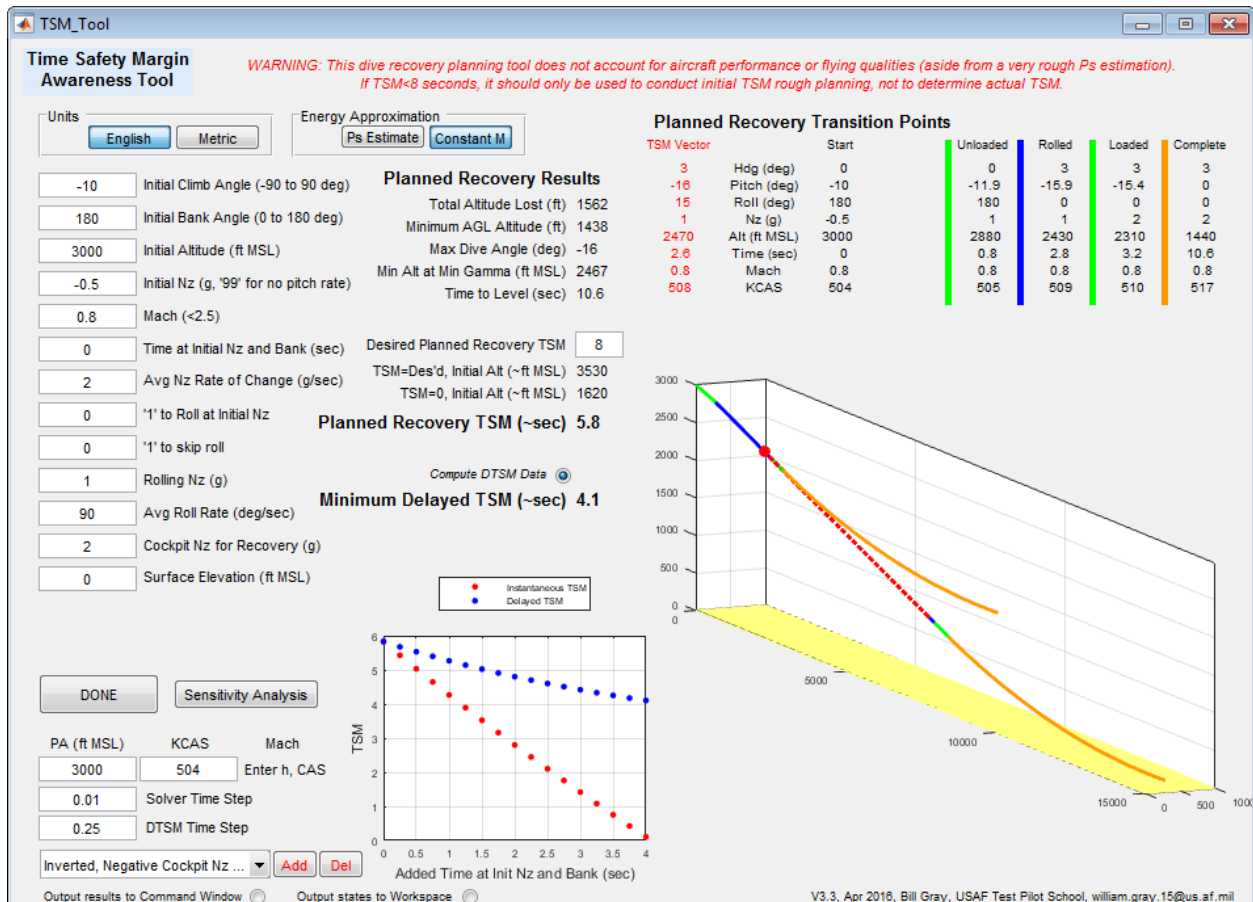
Figure 31 Example: Low Altitude Negative N_z Test Point

T-38 Excess Bank in the Final Turn (Figure 32):

The early history of the T-38 Talon was rife with fatal accidents in the pattern (reference 9). In an overhead pattern, the final turn from downwind to final approach is flown in landing configuration, 20 KCAS faster than final approach speed. About 7 degrees of dive is required to make it to final approach at the right altitude. At these airspeeds the T-38 does not have much N_z available for maneuvering so if the pilot allows the descent rate to become excessive, either by flying too slowly or by using too much bank angle for the N_z, the aircraft can rapidly reach an unrecoverable situation.

We can use TSM (particularly DTSM) to look at the case of excessive bank in the final turn. Figure 32 is set up to roughly approximate a situation where a pilot has recognized tight spacing about one-third of the way through a normal final turn and inadvertently increased the bank angle to 90 degrees while maintaining the N_z required for a 50-degree-bank turn. With no lift countering the weight of the aircraft, it immediately begins to accelerate toward the ground at 1 g. If the pilot immediately recognizes his oversight and recovers, the ITSM is 11.2 seconds; a very comfortable margin. If the pilot fails to recognize the increasing dive angle (the more likely case), the minimum DTSM is just 2.7 seconds; failure to roll out for only 2.7 seconds will result in an unrecoverable dive!

Figure 32 Example: T-38 Over-Banked Final Turn

ADVANCED APPLICATIONS

Time Safety Margin is normally the consequence of a worst-case maneuver; it is something you calculate from a planned condition. But TSM may also be used to help understand t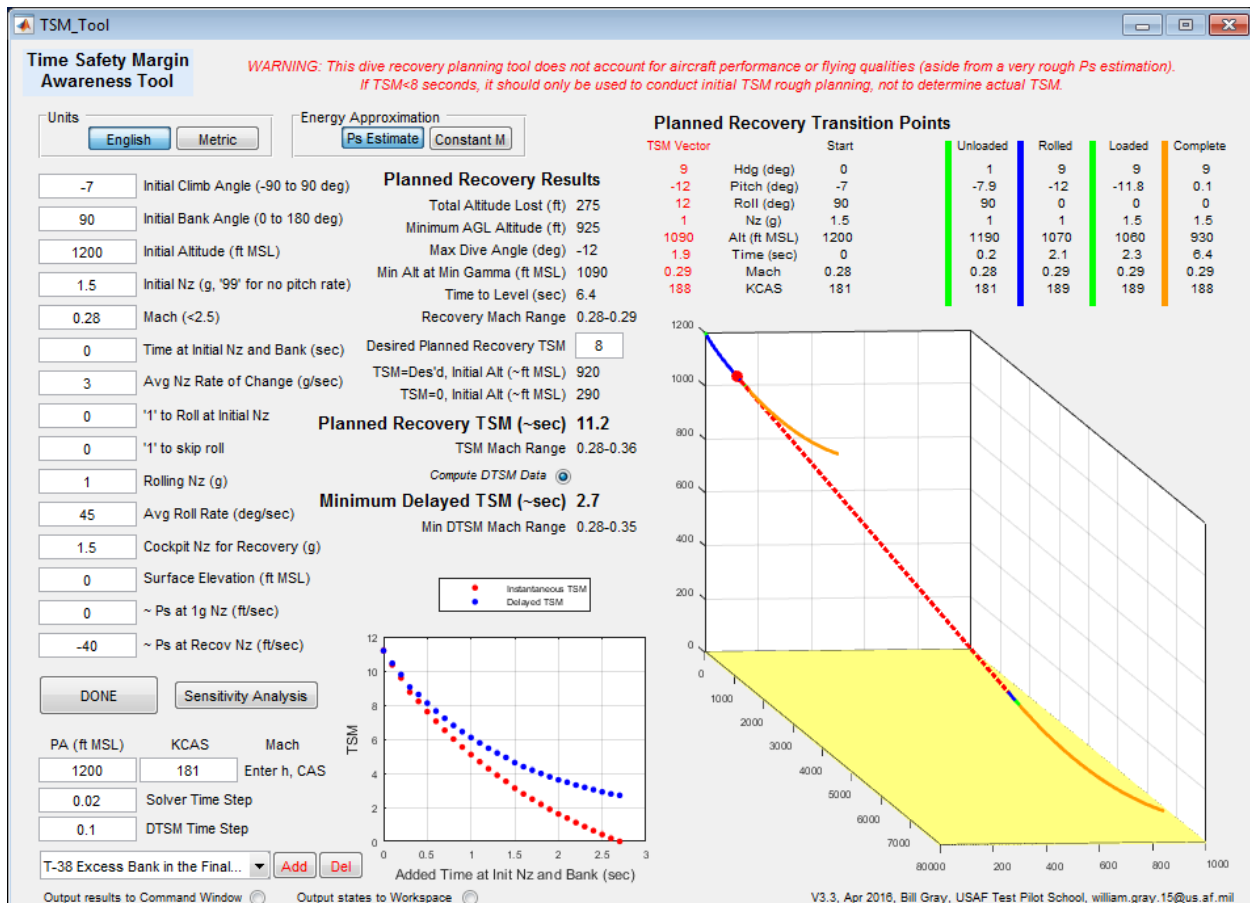he relative risk of pilot errors in an otherwise perfectly routine maneuver. In other words, although TSM is not defined for level flight at 500 ft AGL, it can provide a tool to look at mistakes that will result in a dive. What if the pilot unloads to less than 1 g? How much is too much? How long is too long? If the pilot is turning, what are the consequences of not using enough N_z to keep the aircraft level? By applying DTSM and mapping out the resulting TSM for errors like these, we can gain an appreciation of the relative consequences of various errors.

Low-Level Wings-Level Flight:

Tables 9 and 10 depict how the TSM changes for combinations of cockpit N_z and Mach numbers starting from level flight.[44] If we assume that the aircraft starts in level flight and the pilot immediately unloads, it is clear that the aircraft will eventually hit the ground. How much less than 1 g is too much? By calculating the TSM for a maneuver that starts in level flight at a given N_z, assuming that the pilot immediately perceives the unloaded, increasing dive angle condition, we can calculate the ITSM for the resulting maneuver. Table 9 shows the TSM for this situation; an immediately recognized unloaded condition followed by an immediate recovery. These numbers, all greater than 13 seconds for a wide range of Mach numbers and up to -1 g, indicate that an alert pilot has ample time to recovery from the unloaded condition. These results make low-level flight look much safer than it feels.

Table 9 TSM for a Momentary Wings-Level
Push-Over from 500 Ft AGL

TSM (sec)		Mach Number				
		0.25	0.5	0.75	1	2
N_z (g)	0.5	230.4	230.4	230.4	230.4	230.4
	0.0	59.2	59.2	59.2	59.2	59.2
	−0.5	25.9	25.9	25.9	25.9	25.9
	−1.0	14.0	13.9	13.9	13.9	13.9

Table 10 shows the DTSM for the same situation; in this case depicting how long the push may be maintained until 0 ITSM is encountered and the planned dive recovery results in ground impact. These numbers are much smaller; even a 0.5-g push results in less than 8 seconds of TSM. If the pilot persists in an error—a more likely event since pilots will typically only push forward intentionally—there is very little margin to prevent disaster. These numbers subjectively correlate with the amount of training required for pilots to be qualified for low level flight.

You have probably noted that the TSM and DTSM numbers are essentially the same regardless of Mach number. This is a consequence of the effect of airspeed on the turn rate. At low speed, the aircraft dive angle decreases much more quickly than high speed and the dive recovery for a given dive angle takes less altitude. The faster the aircraft is traveling, the shallower the TSM-defining dive angle.

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[44] $-\gamma_0 = 0$ deg, $\phi_0 = 0$ deg, $h_0 = 500$ feet MSL, $N_{z0} = $ [variable], $M_0 = $ [variable], $t_d = 0$ sec, $\dot{N}_z = 2$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} = 90$ deg/sec, $N_{zr} = 4$ g, $h_S = 0$ feet MSL, constant Mach.

Table 10 Minimum DTSM for a Sustained
Wings-Level Push-Over from 500 ft AGL

Min DTSM (sec)		Mach Number				
		0.25	0.5	0.75	1	2
N_z (g)	0.5	6.8	6.6	6.6	6.6	6.5
	0.0	4.1	4.1	4.0	4.0	4.0
	−0.5	2.9	2.9	2.8	2.8	2.8
	−1.0	2.2	2.2	2.1	2.1	2.1

Low-Level Turning Flight:

We can apply a similar analysis for turning flight. For any given bank angle, there is a cockpit N_z that corresponds to level flight (N_z [in g] $= 1/\cos\phi$) so if the pilot is not at 0-degrees-bank angle at 1 g, the dive angle will be increasing. Tables 11 and 12 depict how the ITSM and DTSM differ for combination of bank angles and Mach numbers starting at 500 ft AGL and 1 g.[45]

Table 11 TSM for Non-Zero Bank Angles at 1 g
(500 ft AGL)

TSM (sec)		Mach Number		
		0.25	1	2
Bank (deg)	60	128.2	128.1	128.1
	75	67.8	67.8	67.7
	90	40.5	40.4	40.4
	135	12.8	12.8	12.8
	180	5.5	5.3	5.3

Table 12 Minimum DTSM for Non-Zero Bank
Angles at 1 g (500 ft AGL)

Min DTSM (sec)		Mach Number		
		0.25	1	2
Bank (deg)	60	6.7	6.2	6.3
	75	5.1	4.6	4.6
	90	3.9	3.7	3.7
	135	2.0	2.2	2.2
	180	1.6	1.3	1.3

As with a wings-level push, the TSM does not look too bad—even for 180 degrees of bank (inverted flight)—because the TSM assumes that the recovery begins with no delay. By adding delay and calculating TSM using DTSM we can see that the time to an unrecoverable condition becomes very short at more than 90 degrees of bank. This conforms well with low-level training rules that often make bank angles in excess of 90 degrees either illegal or only allowed in very specific cases, such as a ridge crossing where the

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[45] $-\gamma_0 = 0$ deg, $\phi_0 =$ [variable], $h_0 = 500$ feet MSL, $N_{z0} = 1$ g, $M_0 =$ [variable], $t_d = 0$ sec, $\dot{N_z} = 2$ g/sec, $N_{z\phi} = 1$ g, $\dot{\phi} = 90$ deg/sec, $N_{zr} = 4$ g, $h_S = 0$ feet MSL, constant Mach.

aircraft must be rolled inverted to prevent excessive altitude gain after climbing with terrain. (During a ridge crossing, the aircraft is typically at a fairly high climb angle and transitioning to descending terrain. This means that there should be adequate margin with proper training and currency.)

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CONCLUSION

Traditionally, pilots have thought of dive recovery margin primarily in terms of minimum altitudes and maximum dive angles. These parameters work for normal operations because most flying involves repetition of routine tasks. Flight test maneuvers often involve procedures that have little operational use but are necessary to investigate particular aspects of an aircraft's characteristics. These procedures are in no way routine, nevertheless the standard dive recovery conventions can provide a sense of comfort when none is warranted. By quantifying the essence of what really matters—the time the test team has to err in the worst-case condition and at the worst-case recovery initiation point—Time Safety Margin serves as a metric that can be used to determine a consistent and accurate measure of safety margin for both conventional and unconventional diving maneuvers. At the AFTC, TSM has improved test efficiency by setting a universal standard for "routine" dives. This standard has substantially reduced the amount of time and effort put into dive planning and buildup for shallow dives conducted below traditional minimum altitude restrictions. Time Safety Margin has also been successfully used for complex dives at very high speeds, encouraging test teams to find procedures, recoveries, techniques, and locations that increase TSM. Finally, TSM provides a clear path to risk minimization and approval for elevated-risk points. There are, no doubt, further improvements that may be made to TSM methodology, but TSM as implemented at the AFTC has been found to encourage and enable rational, effective, and efficient risk reduction measures.

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APPENDIX A – CHARTS FOR ESTIMATING 8 SECONDS OF TSM

Time Safety Margin provides a very convenient and effective method for identifying, understanding, and controlling risk during diving maneuvers, but attempting to accurately determine TSM can produce severe over-planning for dives with a very high TSM.

These figures provide one way around spending too much time finding TSM when TSM will clearly not drive additional dive planning (generally, when it is 8 seconds or more).[1] These figures show the AGL altitude that corresponds to 8 seconds of TSM for a variety of bank angles and recovery load factors. Constant Mach is assumed throughout with with Mach 0.15 through Mach 2 provided in the charts. Unplanned delay past the planned recovery worst-case condition is assumed to be nil; *these charts do not account for DTSM.* If the planned test procedure and recovery clearly lie within the assumptions for these charts and the planned minimum recovery start altitude is less than that shown for 8 seconds of TSM, then TSM planning should be considered complete.

These constant-Mach figures are divided into three sets; wings-level dives, 90-degree bank-angle dives, and inverted dives. The constant-Mach assumption works very well for dive recoveries that do not take much time, such as shallow dives and high N_z dive recoveries. Longer dive recoveries—taking as long as 75 seconds for a 1.5-g recovery from 90-degrees dive angle at 50,000 feet—small deviations from the recovery assumptions can significantly reduce the predicted TSM. Engineering judgment is required; as the planned minimum altitude/Mach number gets close to the 8 second TSM line, the potential for producing an actual TSM significantly less than 8 seconds increases with Mach number, altitude, and reduced recovery N_z.

Figures A1 through A4 show the Mach/AGL altitude combinations for wings-level dives across a variety of dive angles. These charts assume that the dive recovery is begun at a steady-state condition (constant dive angle, constant Mach) and the recovery is accomplished at constant Mach using the N_z and N_z rate depicted in the figure.

Figures A5 through A8 show the Mach/AGL altitude combinations for a variety of dive angles when the initial bank angle is 90 degrees and the initial N_z is the same as the recovery N_z. Each of these charts is for a different recovery N_z; the average roll rate and N_z rate is reduced with the recovery N_z to roughly equate to the reduced roll rates and N_z onset rates that might be expected for aircraft with relatively low recovery N_z capacity. The odds of an actual test point meeting these parameters is very small, but by choosing a clearly conservative situation in the figures and showing that the planned recovery altitude is greater than the predicted 8 second TSM altitude shown in the figure, a planner can confidently claim that at least 8 seconds of TSM is available and that TSM planning is complete. These charts only provide the estimated TSM with no unanticipated recovery delay. At 90-degrees angle-of-bank the dive angle will be increasing and ITSM will be decreasing slightly faster than one second per second so the effect of unplanned delay should be considered.

The last three figures, A9 through A11, show the Mach/AGL altitude combinations for 8 seconds of TSM in a variety of dive angles during inverted flight. These predictions assume that the N_z for the initial maneuver is equal to the recovery N_z. As with the 90-degree bank-angle charts, the roll rate and N_z rate of change are reduced with reduced recovery N_z to make the performance characteristics more consistent. Inverted recoveries have an interesting complication; there are two typical recoveries that may be used and each one is "best" for a different range of initial dive angles. The optimum recovery for shallow dives

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[1] This follows from the idea that 8 seconds of TSM is typical of the minimum margin routinely used in basic operational flying by qualified pilots. With this much margin, you should be able to rely upon operationally-developed judgment for dive recovery safety.

is called a nose-low recovery (NLR in the figures). It entails unloading to an N_z suitable for rolling—typically 1 g—rolling "to the nearest horizon" (rolling to 0-degrees bank angle), then pulling to a suitable N_z for recovery. This recovery minimizes altitude loss—and maximizes TSM—for shallower dive angles but the act of unloading, rolling, and loading back up also loses significant altitude. If the dive angle is steep enough (about 70-degrees dive for fighter-type performance) the altitude loss will be minimized and TSM maximized by just continuing the pull until recovery. (This is called a split-s recovery; "SSR" on the figures.) The lines on these figures associated with each depicted dive angle are, therefore, divided into two parts. At lower Mach numbers TSM is maximized by just continuing the pull until recovery. This is thanks to the increasing turn rate for a given N_z as Mach number is decreased. The "knee" in each dive angle line corresponds to the Mach at which the NLR and and the SSR both produce a TSM of 8 seconds. At higher Mach numbers the NLR is optimum and at lower Mach numbers, the SSR is optimum. Thanks to the elevated positive N_z in inverted flight, the minimum DTSM for these maneuvers may be significantly less than the TSM depicted on the figures; thus these figures should be used with caution. If DTSM will be used as the method for calculating TSM, the minimum DTSM will never be greater than 8 seconds if the starting altitude is below the "90° Dive, SSR" line.

8.0 Second TSM Estimate for 1.5 g Constant Mach Recovery

Wings-level steady-state dive, 1.5 g in 3 seconds with
no delay, constant Mach, 8 sec TSM,
dTSM/dt for unplanned delay = -1 sec/sec

True Mach Number

Altitude (ft MSL, std day, sea level surface)

90° Dive
60° Dive
45° Dive
30° Dive
20° Dive
10° Dive
5° Dive

Figure A1 Eight Second TSM Estimates for a 1.5-g Recovery from a Wings-Level Dive

Figure A2 Eight Second TSM Estimates for a 2-g Recovery from a Wings-Level Dive

Figure A3 Eight Second TSM Estimates for a 3-g Recovery from a Wings-Level Dive

Figure A4 Eight Second TSM Estimates for a 6-g Recovery from a Wings-Level Dive

Figure A5 Eight Second ITSM Estimates for a 2-g Recovery from a 2-g 90-degree Bank Dive

Figure A6 Eight Second ITSM Estimates for a 3-g Recovery from a 3-g 90-degree Bank Dive

Figure A7 Eight Second ITSM Estimates for a 4-g Recovery from a 4-g 90-degree Bank Dive

Figure A8 Eight Second ITSM Estimates for a 6-g Recovery from a 6-g 90-degree Bank Dive

Figure A9 Eight Second ITSM Estimates for a 3-g Recovery from a 3-g Inverted Dive

8.0 Second TSM Estimate for 4.0 g Constant Mach Recovery from 180° Bank Angle

180 deg bank dive at 4 g, optimum recovery is split-s (SSR) or standard (NLR, roll at 1 g, roll rate is 60 deg/s, load/unload at 1.5 g/sec), constant Mach, lines depict 8 sec TSM, dTSM/dt for unplanned delay > -1 sec/sec

Altitude (ft MSL, std day, sea level surface)

True Mach Number

Legend:
- 90° Dive, SSR
- 60° Dive, SSR
- 45° Dive, SSR
- 30° Dive, SSR
- 15° Dive, SSR
- 0° Dive, SSR
- 60° Dive, NLR
- 45° Dive, NLR
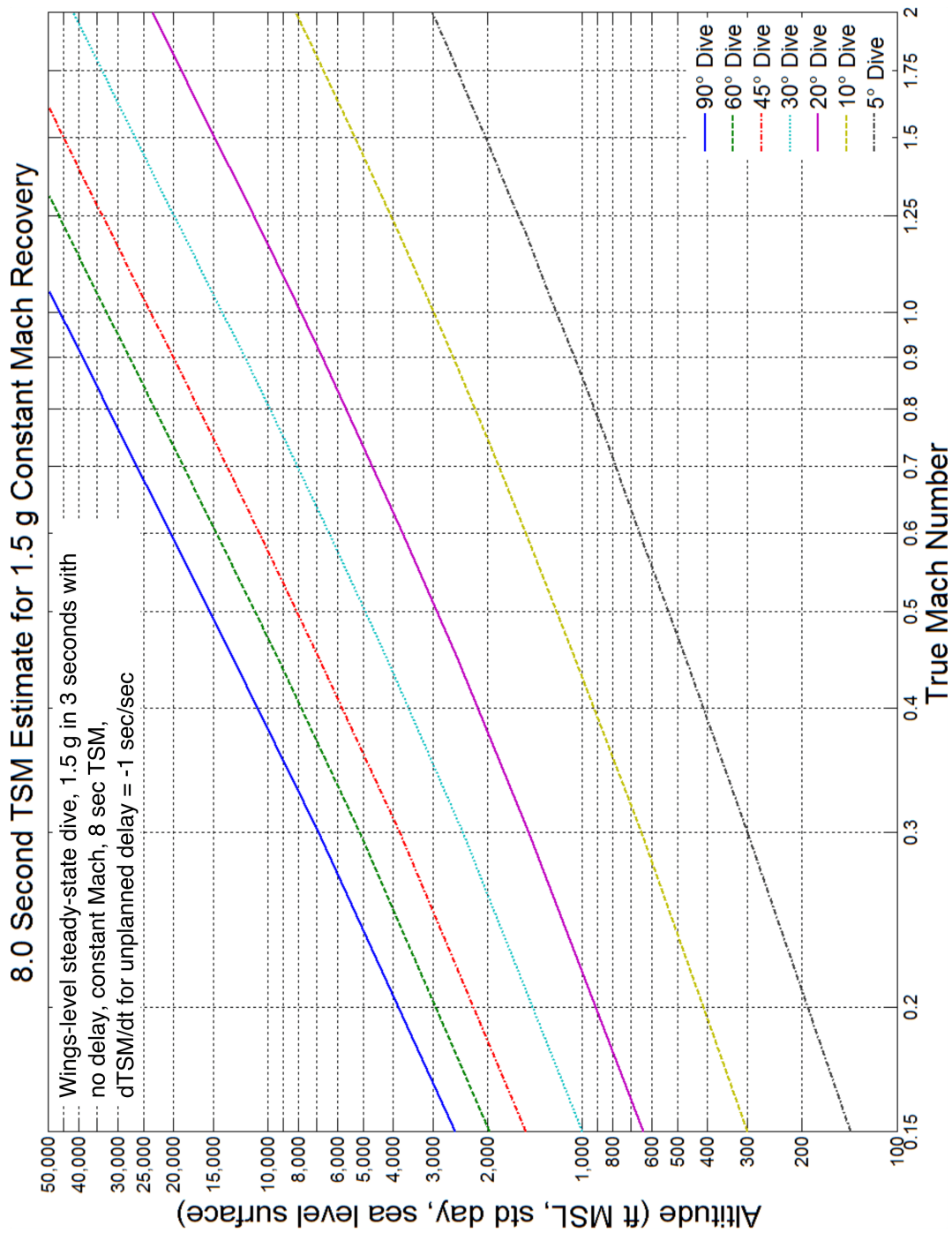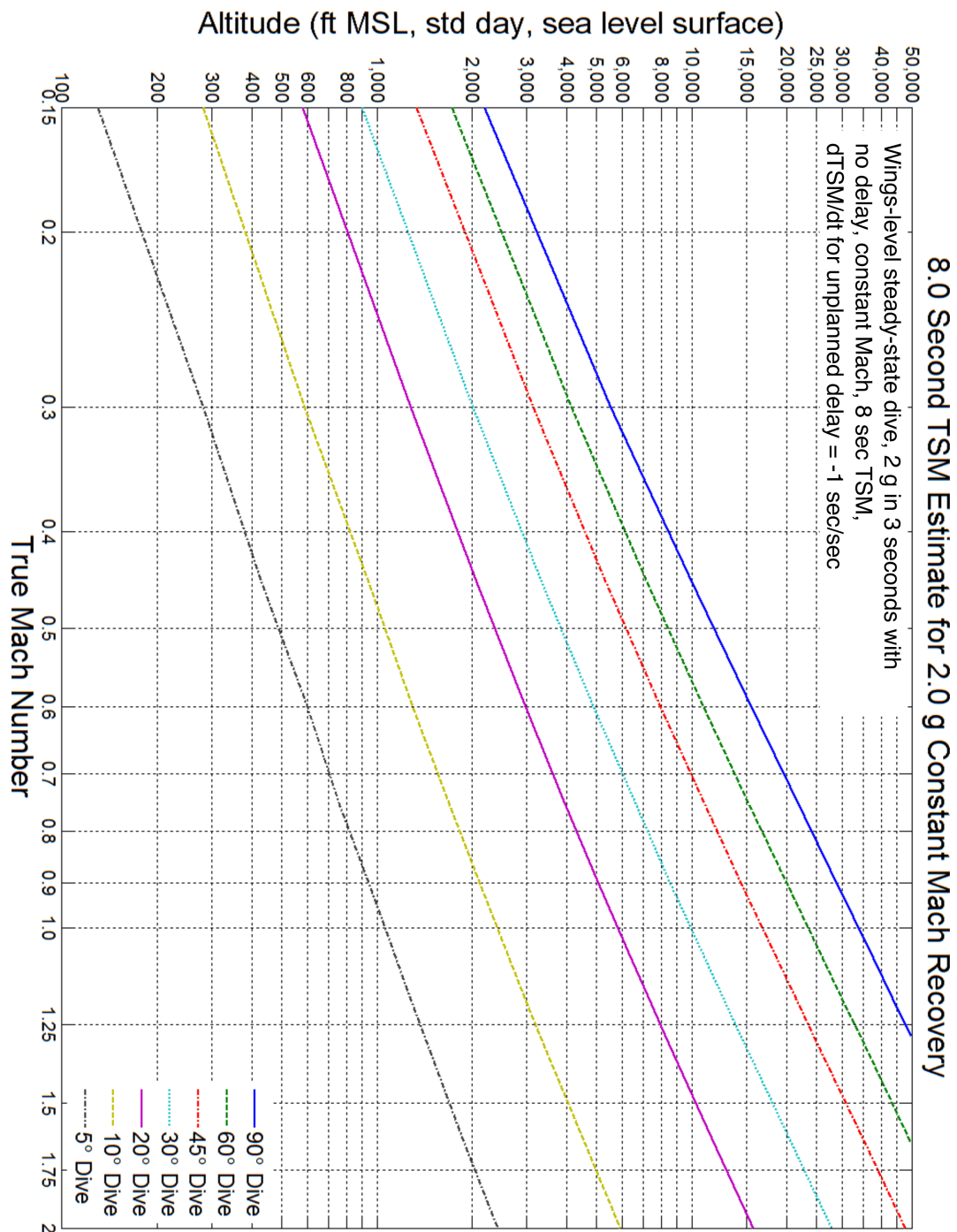- 30° Dive, NLR
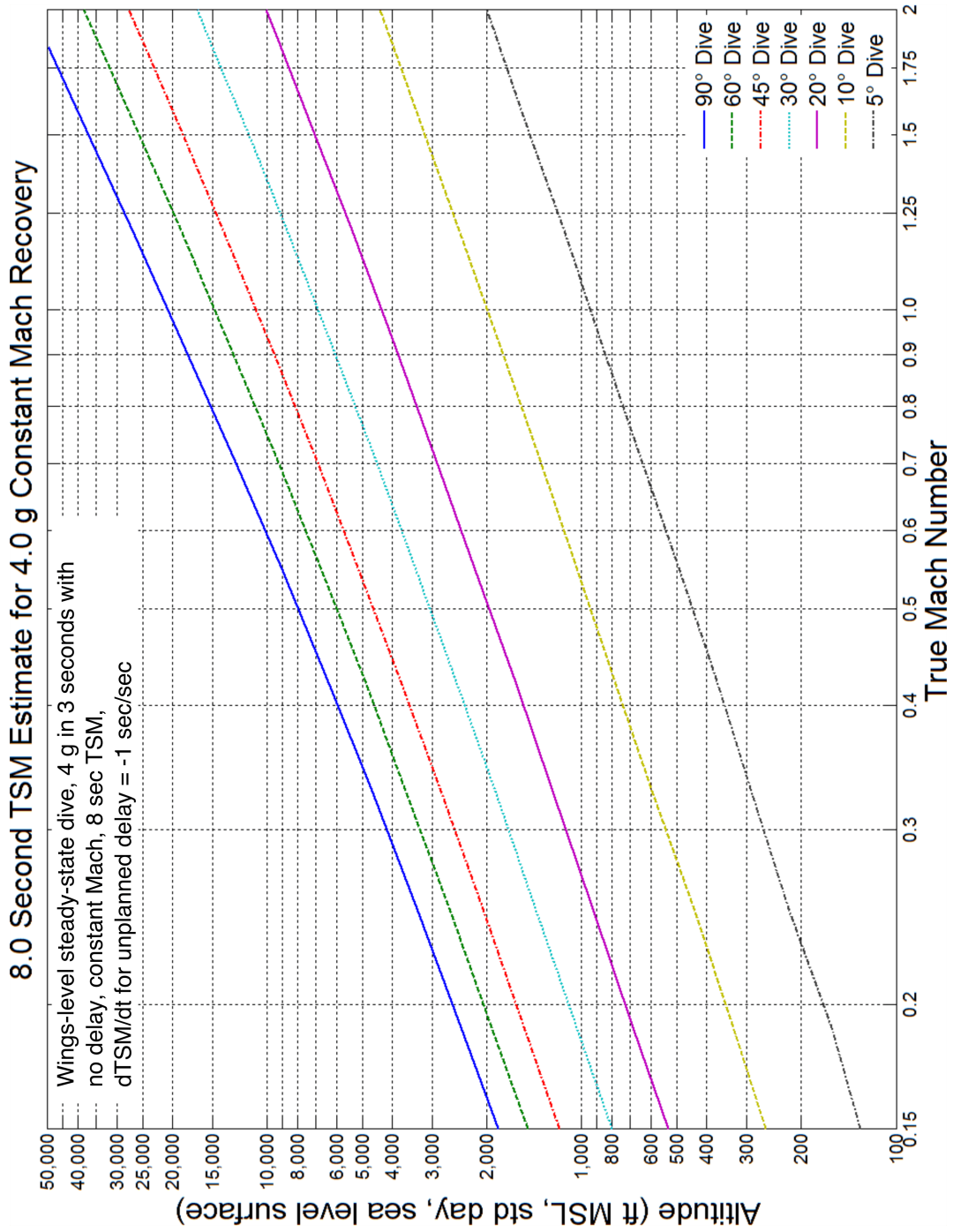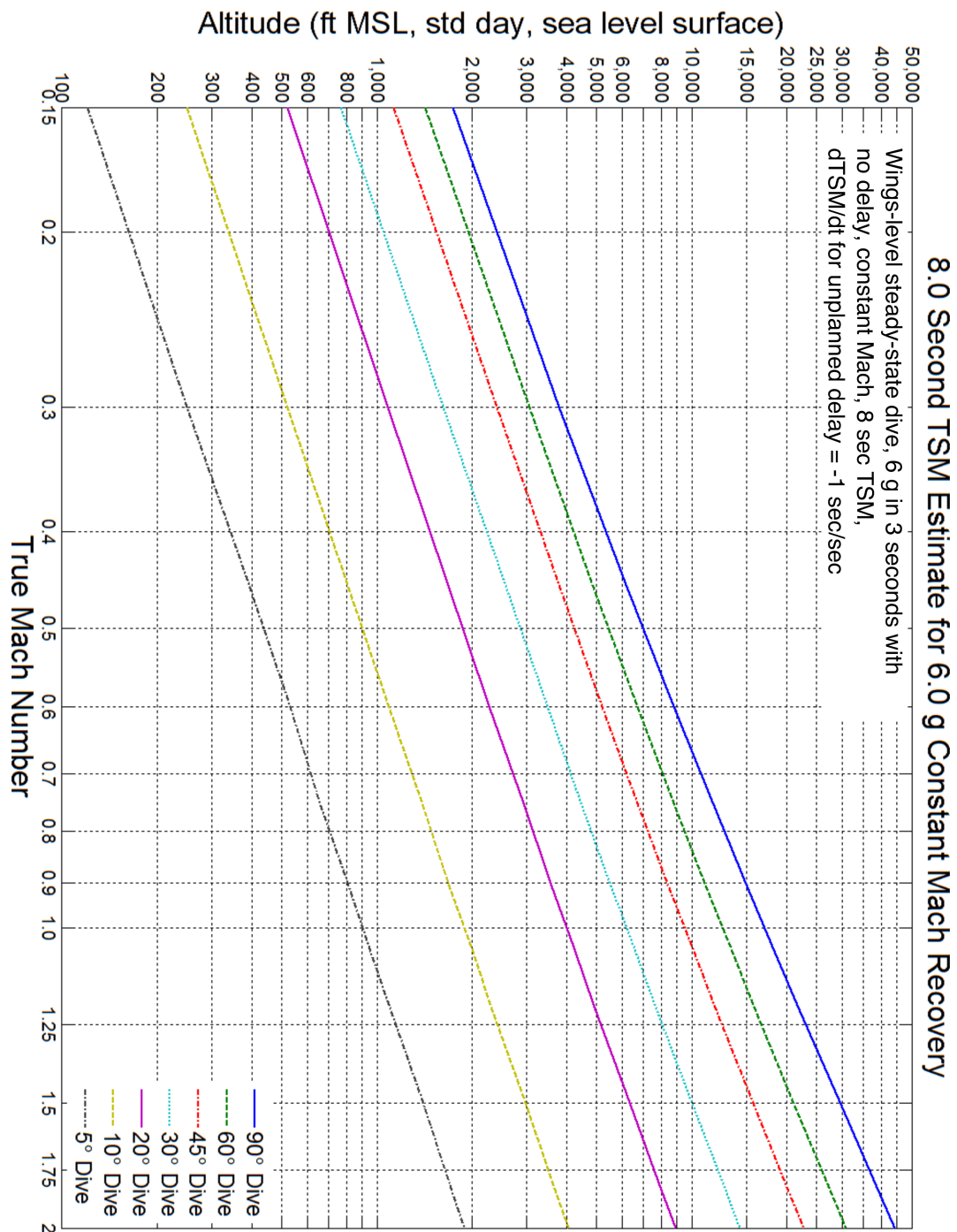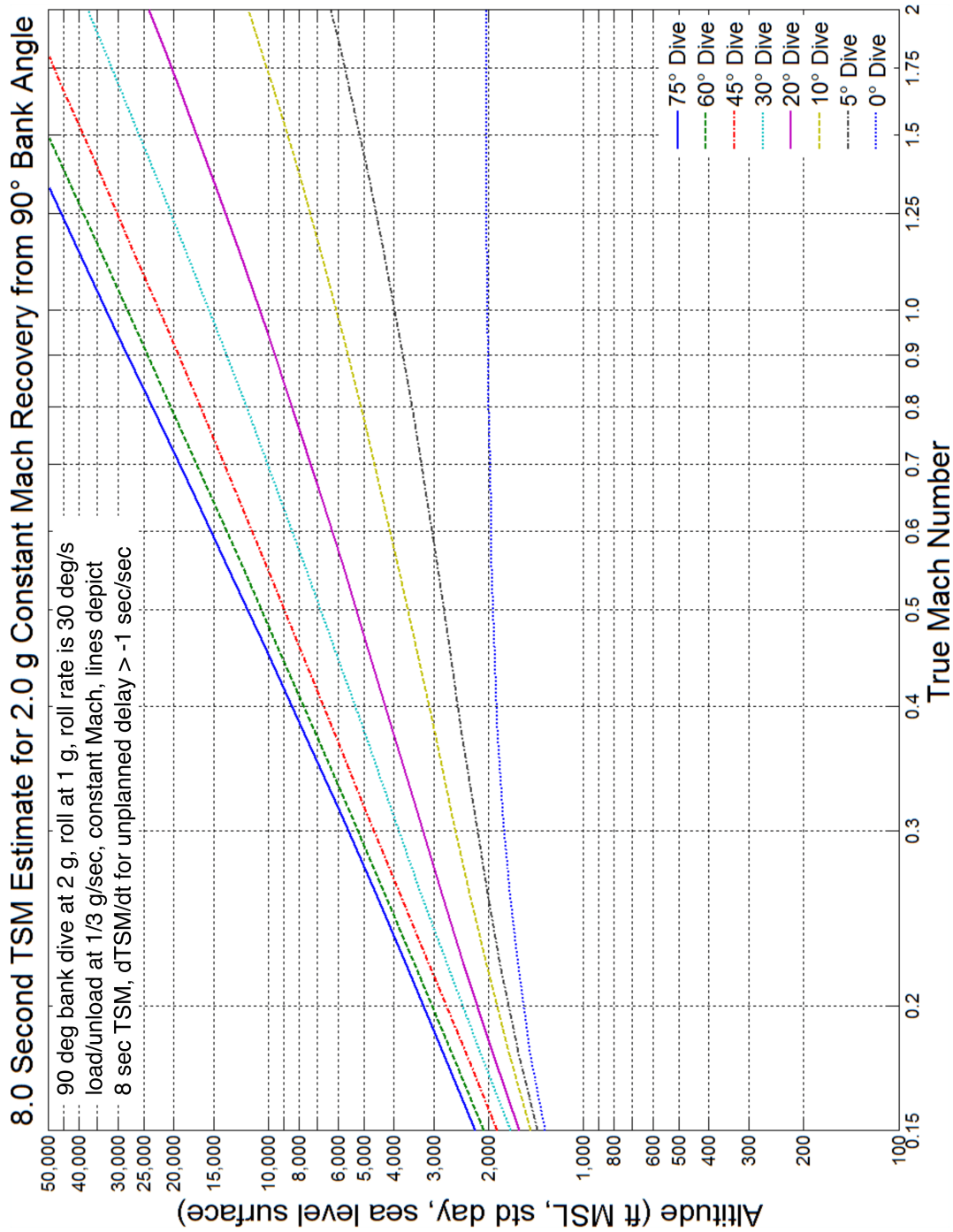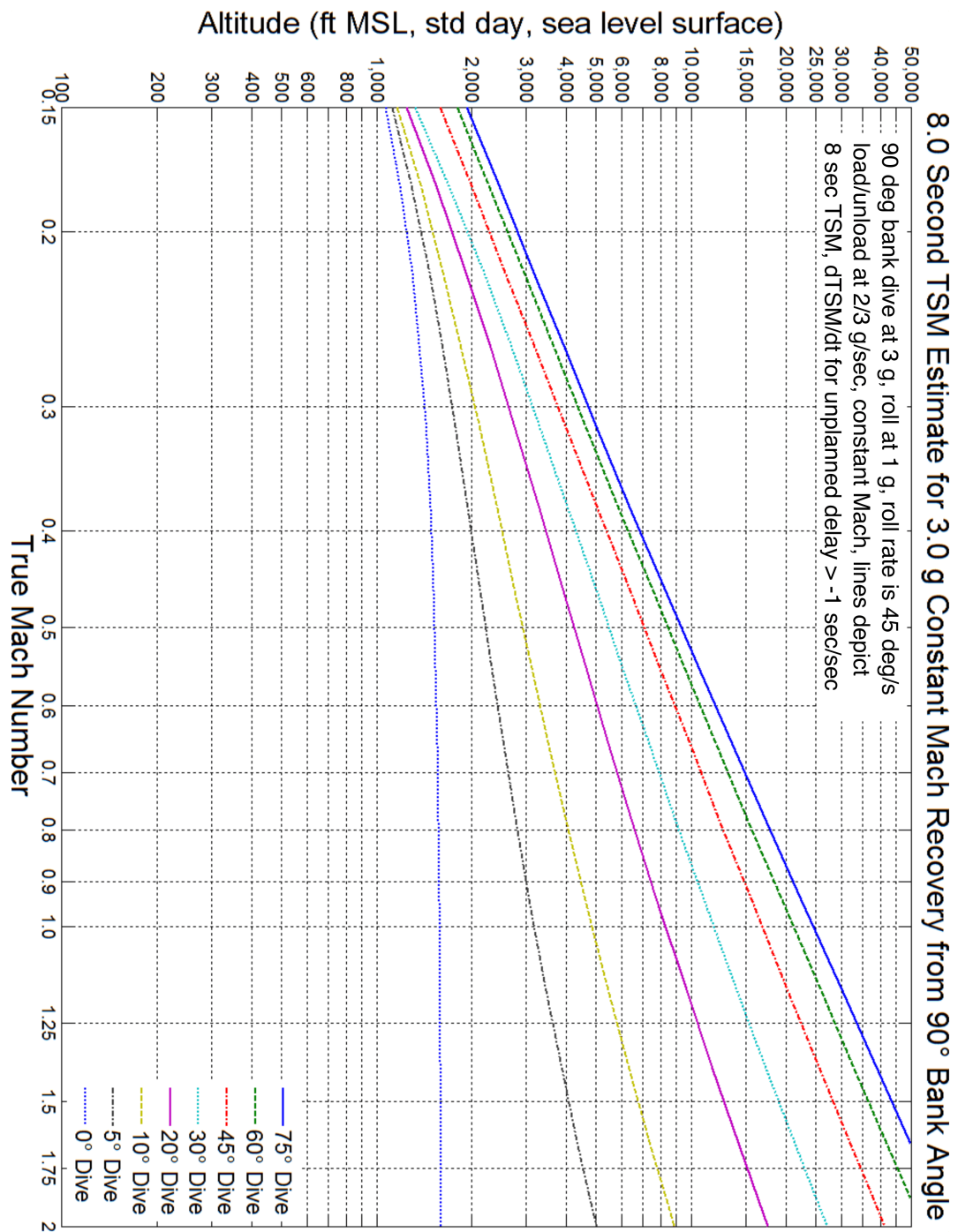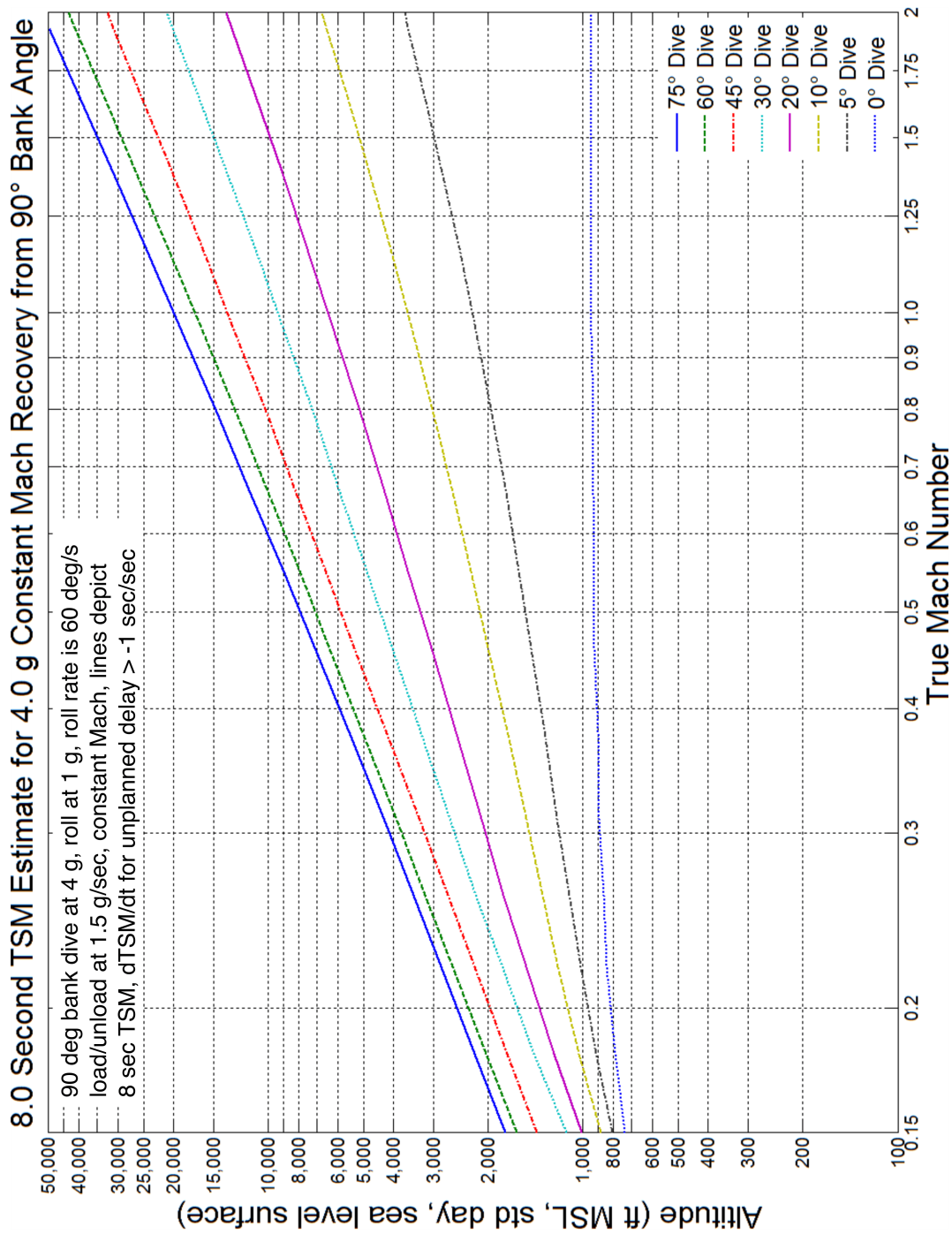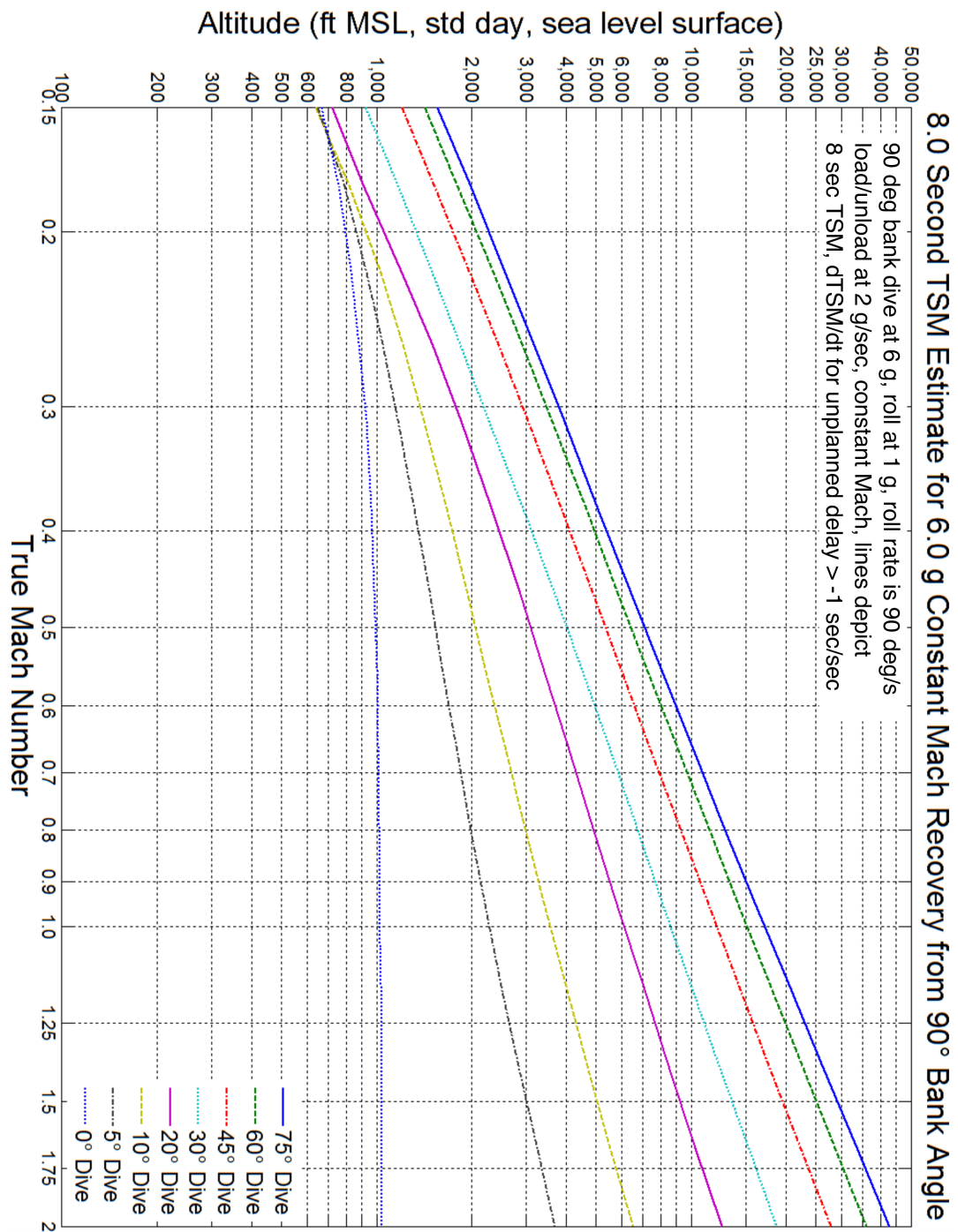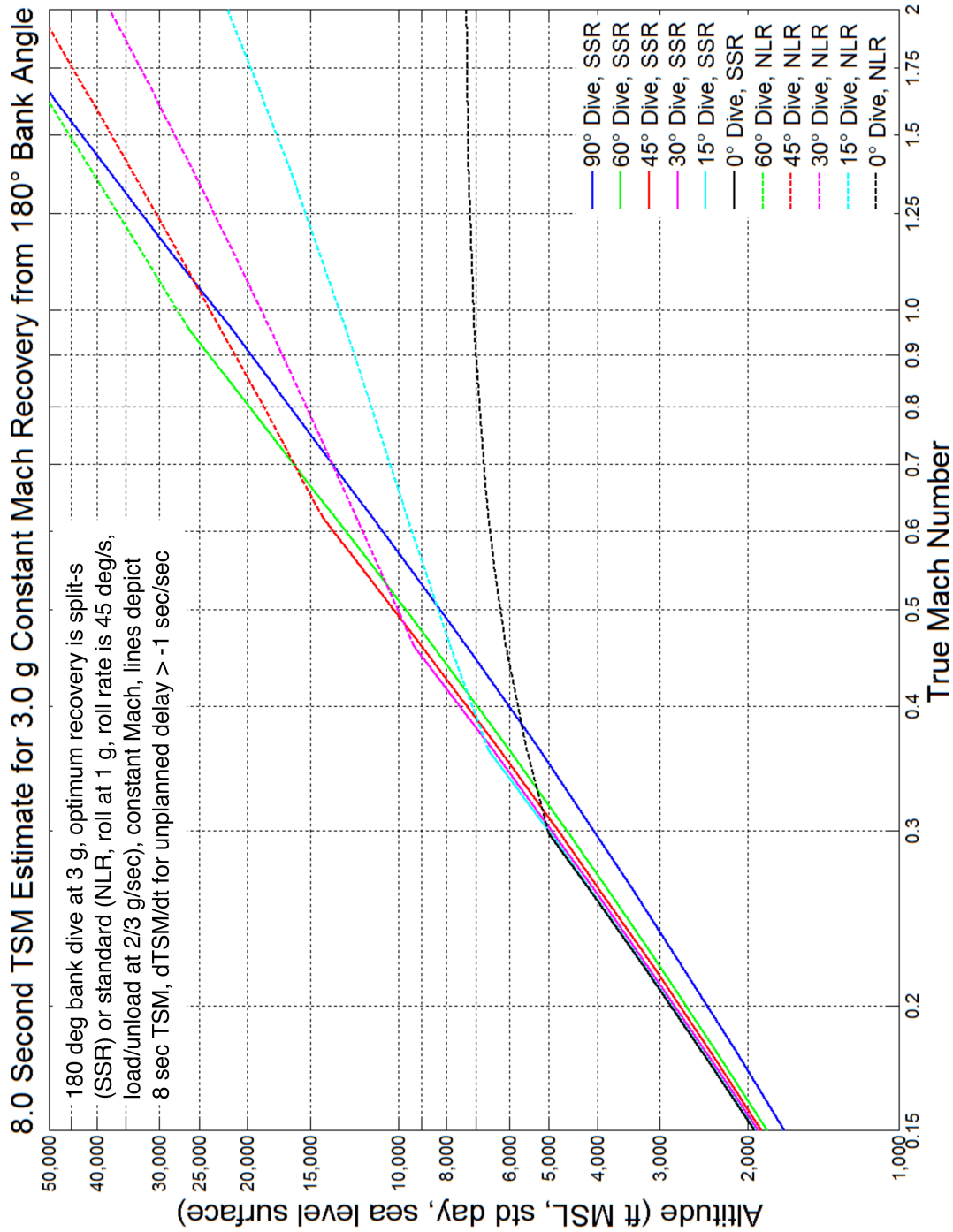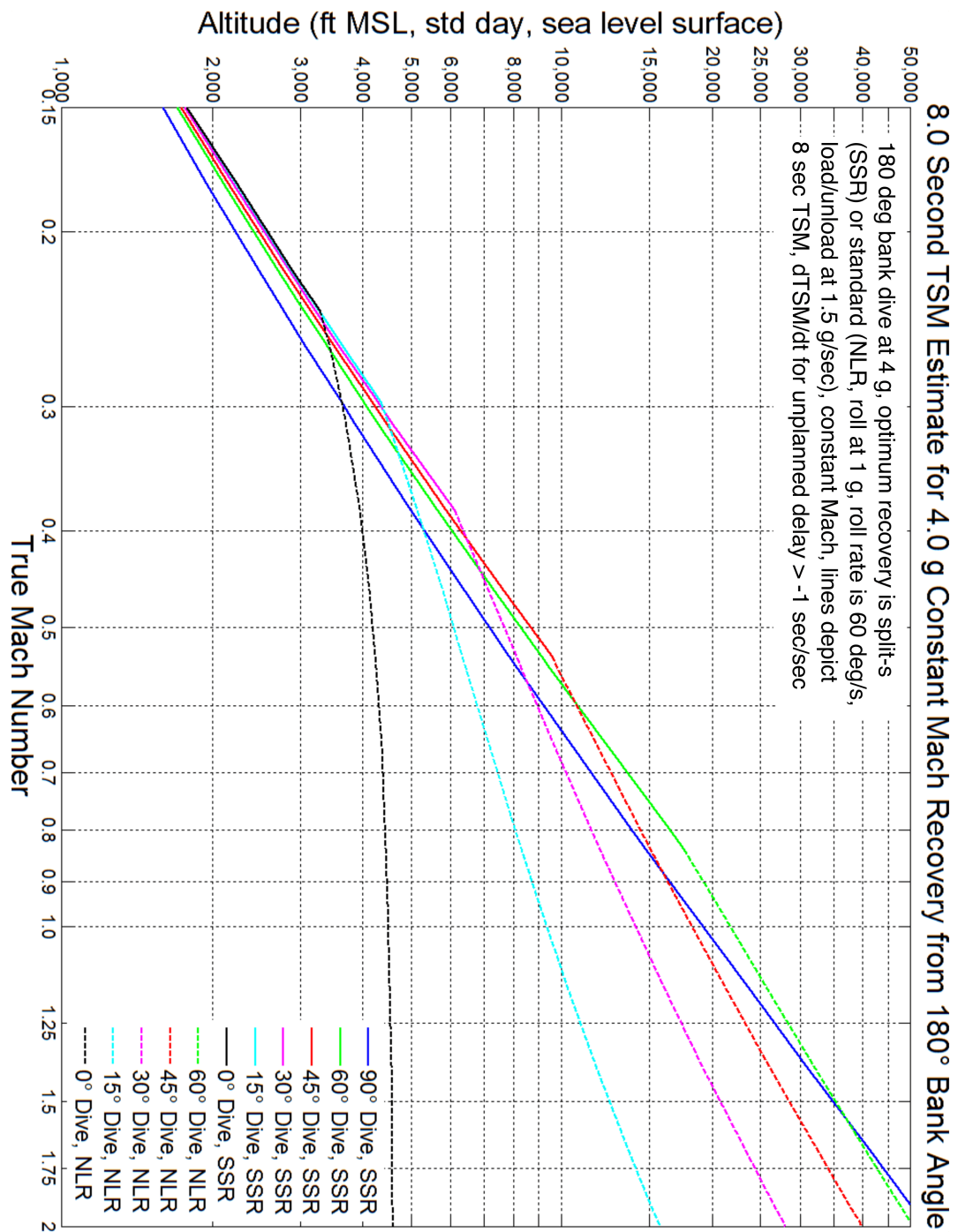- 15° Dive, NLR
- 0° Dive, NLR

Figure A10 Eight Second ITSM Estimates for a 4-g Recovery from a 4-g Inverted Dive
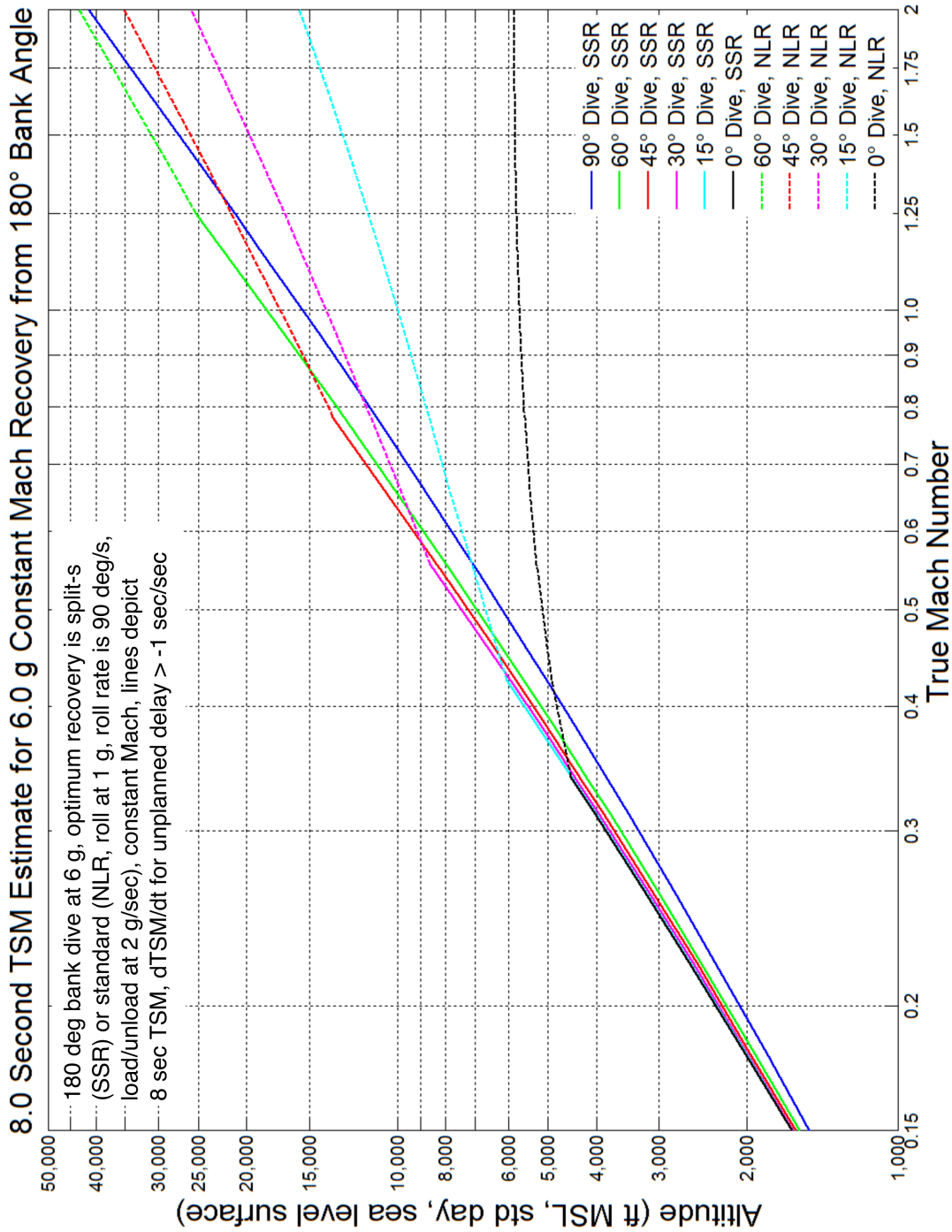
A-12

Figure A11 Eight Second ITSM Estimates for a 6-g Recovery from a 6-g Inverted Dive

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APPENDIX B – DRAFT CHANGE TO AFMC TSM REQUIREMENTS

As the Test Information Handbook *Time Safety Margin: Theory and Practice* was progressing through the final approval stages, an update was proposed to the AFMC requirements regarding the application of TSM to USAF developmental test and evaluation. This appendix contains the relevant text of the draft change to AFI 11-2FT Volume 3 *Flight Test Operations Procedures*[1] as it progressed to the USAF Headquarters approval process in July 2016.

INTRODUCTION

The exact text of the change is provided to show the evolution of TSM requirements in AFMC. The changes in this draft were based primarily on lessons-learned from years of TSM application across AFMC, including:

- **Scope of the Test Maneuver:** When TSM was applied only to the specific test maneuver, the maneuver setup might be ignored even though it could have a much lower TSM. For instance, if a steep dive was planned to achieve the airspeed for a high-speed low-altitude shallow dive and TSM planning was focused solely on the shallow dive of the test point, dive planning for the setup could be inadvertently ignored. (See paragraph 3.16.15.1.1. in the draft text.)

- **TSM Decreasing Faster than One Second per Second:** This risk element was not taken into account in the original definition of TSM. Delayed TSM will meet this requirement. (See paragraph 3.16.15.1.2. in the draft text.)

- **Presumed Risk Assessment:** The presumed risk assessment levels of the original TSM requirements produced significant unintended consequences. The most important consequence was that the risk assessment became a function of the TSM, often with no consideration taken for risk mitigation beyond the baseline requirements for the TSM. This led some test organizations to use informal rules disallowing test maneuvers with less than four—or even eight—seconds of TSM. These rules either increased the cost of a test program by requiring test points to be conducted much further from the home field (to take advantage of lower terrain elevation) or—more ominously—foreshortened envelope expansion by preventing investigation of the lower-right-hand corner of the envelope. The change makes it clear that the presumed risk mitigation levels only apply to maneuvers where no risk mitigation has been applied. It is up to the SRB to determine the residual risk with the mitigation applied. In addition, the presumed *no-mitigation* risk assessment levels were raised from the earlier presumed risk assessment levels. The earlier levels assumed that the required risk reduction methods were employed. Without risk reduction, the risk is clearly increased. (See table 3.3 in the draft text.)

- **Cued Anticipation:** The first iteration of AFFTC TSM requirements recommended an automatic recovery system for any test point with less than 1.5 seconds of TSM. The first AFMC iteration of these requirements prohibited any test maneuver with less than 1.5 seconds of TSM. Neither of these requirements took into account operational maneuvers such as low-angle strafe or airshow demonstrations. These maneuvers often use anticipatory cueing to allow pilots to reliably recover with less than one-tenth of a second of delay during maneuvers with less than 1.5 seconds of TSM. (See table 3.3 in the draft text.)

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[1] HQ AFMC/A3V, Wright-Patterson AFB, Ohio, November 2011

AFI 11-2FTV3 "FLIGHT TEST OPERATIONS PROCEDURES" DRAFT TSM REQUIREMENTS

The draft change is provided here for reference only.

3.6.15. Time Safety Margin (TSM).

3.6.15.1. For test points involving descents/dives that are not conducted IAW AFI 11-2FTV3, AFTTP 3- series publications, or the sections of AFI 11-214 invoked by this AFI, base recovery planning and risk management upon the calculated TSM. TSM is the time in seconds to directly travel from the worst case vector (i.e. worst case combination of parameters: dive angle, attitude, airspeed, and available G that includes both planned and maximum allowed deviation/tolerance) to an unrecoverable condition. Use the following general planning factors and limits when calculating TSM.

3.6.15.1.1. The worst-case vector may occur at any point during the entire maneuver, from the FTT setup to the completion of the recovery. For instance, the worst-case vector may be during FTT setup if a steep dive is used to gain airspeed for a FTT conducted in a shallow dive.

3.6.15.1.2. When the dive is becoming steeper at the dive recovery initiation point, the TSM is decreasing faster than 1 second for every second of delay. Test teams must account for this additional risk element.

3.6.15.1.3. Calculate abort/recovery procedures using no more than 90% of available aircraft limits and performance characteristics (i.e. roll rate) at the flight conditions or 90% of the flight clearance authorized G loading, whichever is less. Additionally, minimize any combination of high-G, G dwell time, high-G onset, roll rate, and rapid transition from negative to positive G.

3.6.15.1.4. Normal-G onset rate will be in accordance with aircraft capabilities at the test conditions.

3.6.15.1.5. Brief all normal-G levels, roll rates and other assumptions used to calculate maneuver TSM to the technical and safety review boards.

3.6.15.1.6. Use the procedures outlined in Table 3.3 to minimize the risk of controlled flight into terrain (CFIT) cognizant that the charted risk assessment is prior to mitigation.

3.6.15.1.7. Regardless of the TSM, test teams must be alert for situations that may require additional risk mitigation. High G, poor visibility, pilot distraction on mission systems, G-induced loss of consciousness (GLOC), and unanticipated engine and aerodynamic characteristics may make it impossible to perform the planned recovery.

Table 3.3. TSM Risk Assessment

Risk Mitigation Standards	Routine (TSM ≥ 8 sec)	Focused (8 sec > TSM ≥ 4 sec)	Aided (4 sec > TSM ≥ 2.5 sec)	Redundantly Aided (2.5 sec > TSM ≥ 1.5 sec)	Cued Anticipation[1] (1.5 sec > TSM ≥ 0 sec)
Minimum Planning Fidelity[2]	IAW Normal Operations	M&S[2]	Best Available M&S[2]	Best Available M&S[2]	Best Available M&S[2]
Recovery Procedure[2,3]	Routine[4]	Defined & Documented[5]	Defined & Documented[5]	Defined & Documented[5]	Defined & Documented[5]
Minimum Training & Buildup[6]	Not Required	In-Flight Buildup[6]	Sim Rehearsal[7,8] & In-Flight Buildup[6]	Sim Rehearsal[7,8] & In-Flight Buildup[6]	Sim Rehearsal[7,8] & In-Flight Buildup[6]
Recovery Initiation Call	Pilot	Pilot	Backup for Pilot[9,10]	Two Backups for Pilot[9,10,11] & Anticipatory Cueing Desired[1,9,12]	Backup for Pilot[9,10] & Anticipatory Cueing Required[1,9,12]
Presumed No-Mitigation Risk Assessment[13]	Low	Medium	High	Very High	Excessive[14]

Notes:

1. Anticipatory cueing provides a timeline to recovery, e.g. Automatic Ground Collision Avoidance System (AGCAS) Heads-Up Display (HUD) "chevron" symbology or altitude countdown.

2. Brief the SRB on all available modeling and simulation (M&S) tools and which was used for TSM planning. The SRB will validate both the dive planning M&S and the planned recovery procedure.

3. Calculate abort/recovery procedures using no more than 90% of available aircraft limits and performance characteristics (i.e. roll rate) at the flight conditions or 90% of the flight clearance authorized G loading, whichever is less. Additionally, minimize any combination of high-G, G dwell time, high-G onset, roll rate, and rapid transition from negative to positive G.

4. Initiate recovery immediately after the test point is complete.

5. Document the planned and worst case allowable parameters, abort parameters and recovery procedure on flight test cards.

6. Accomplish initial in-flight buildup maneuvers with a minimum TSM of 8 seconds to validate predictions before proceeding to the test condition.

7. Simulator rehearsals will include practicing the complete recovery procedure.

8. Establish crew and critical test team member maneuver currency as part of the test and safety review process.

9. All available onboard altitude awareness devices will be briefed and used. To eliminate confusion as to what constitutes an "available" device, the test and safety planning process will define the minimum required onboard devices.

10. The recovery initiation back-up may be provided by an on-board safety crewmember, a chase aircrew, or control room personnel.

11. At least one of the two recovery initiation back-ups must be external to the test aircraft. Anticipatory cueing may be used as one of the two pilot backups in the Redundantly Aided column.

12. The recovery cueing system must be fully qualified prior to flight then checked immediately prior to the maneuver. Human intervention to back-up the cueing system may not be considered risk mitigation for less than 1.5 seconds of TSM. An automatic recovery system may be used, but anticipatory cueing should still be provided.

13. Risk assessment should be based upon the anticipated effectiveness of the risk mitigation plan. With no risk mitigation aside from routine operations the risk assessment should not be less than that given in this row. The mitigated TSM risk level is at the discretion of the SRB.

14. Without anticipatory cueing, CFIT is probable.

APPENDIX C – USER MANUAL FOR THE "TSM AWARENESS TOOL"
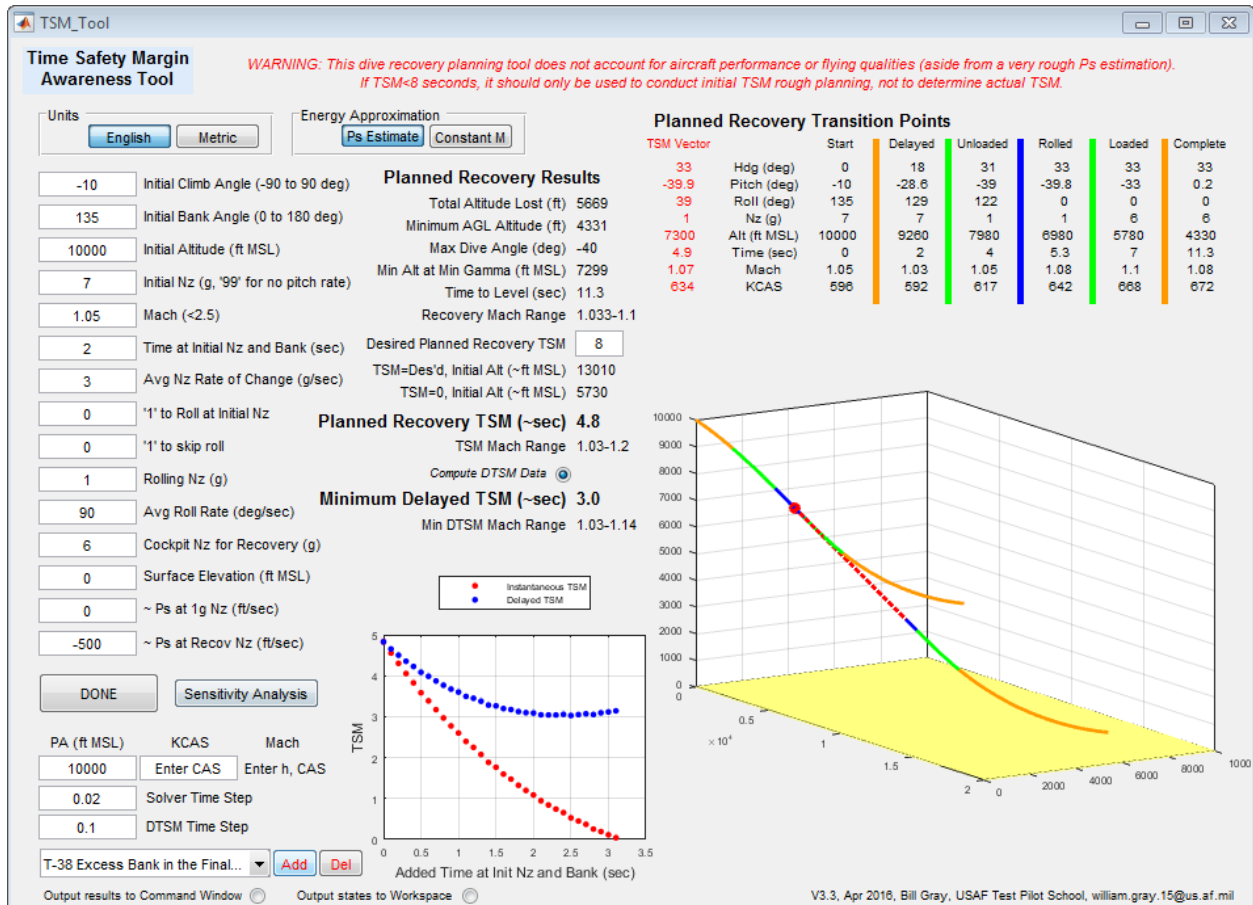
OVERVIEW

The Time Safety Margin Awareness Tool is a Matlab graphical user interface (GUI) developed to aid in the initial development of diving maneuvers by providing an aircraft-independent calculation of TSM in a way that will be useful for the majority of potential maneuvers. The tool may be used with English or metric units. The user may choose either a simple energy approximation or constant Mach for the maneuver. Once the user inputs the parameters for the maneuver and recovery, the tool calculates the planned recovery TSM (TSM) and delayed TSM (DTSM) and provides information on the recovery maneuver including a graphical depiction of the recovery and the TSM-defining scenario. The change in TSM with delayed recovery is also provided in graphical format. The user may save, select, or delete scenarios.

As TSM gets small enough to require risk mitigation greater than routine pilot actions (generally interpreted as less than 8 seconds) the accuracy of the TSM calculation becomes increasingly important. The TSM Awareness Tool may reasonably be used for determining TSMs greater than 8 seconds because the simplifications and assumptions will generally result in errors of much less than 8 seconds. The tool should not be considered adequate for meeting TSM planning requirements when the TSM may be less than 8 seconds but it is useful for initial estimates and maneuver planning.

Standard Dive Recovery Profile:

The TSM Awareness Tool is based upon a series of events that happen in most dive recoveries. The order of these events cannot be changed in the model but some may be skipped. The starting point of a recovery ("start") is defined by the user; including altitude, airspeed, bank angle, dive angle, and N_z. The next step ("delay") allows for the initial N_z with no roll rate command to be held for a specified time.[1] Once this time is over, the "unload" phase is entered as the pilot unloads at the specified g-per-second to the specified rolling N_z. During the "roll" phase the pilot rolls to wings-level flight at the specified average roll rate. The pilot then pulls to the specified recovery N_z during the "load" phase. Finally, the recovery is "complete" when level flight as attained.

There are some very important assumptions that must be considered when using this tool. It assumes that the N_z is not changing and that body-axis roll rate is nil at the start of the recovery or during the unplanned delay. If these do not hold true for the end-point of a planned test procedure, the TSM may be decreasing much more rapidly than this tool will calculate. For instance, a wings-level push to negative N_z, calling for decreasing the N_z by 0.5 g-per-second to a limit of -1.0 g, could overshoot the limit should the recovery be delayed. As the actual N_z decreases below -1.0 g, the TSM will rapidly decrease to less than the TSM calculated by the tool. Carefully choose a worst-case bank angle and N_z that take into account dynamic overshoot during the recovery.

Notes on Running the Software:

The Matlab code in the TSM Awareness Tool is a melange of new code, recycled functions, and off-the-shelf routines. It began as a means to quantitatively experiment with dive recovery dependencies and steadily evolved into its current form. Results from the TSM Awareness Tool have been qualitatively compared to a range of actual dive recoveries and match well.

Those with Matlab experience will find running the code quite easy. After opening Matlab, navigate to the folder containing the supplied files and enter "TSM_Tool" in the command window. The GUI should immediately start up.

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[1] The Euler roll angle will change during this time if the aircraft is not at 0 or 180-degrees bank angle.

Preset scenarios are kept in a file called "presets.mat." The format of this file is important so—unless you are very comfortable with Matlab—you should only use the GUI to make changes to the file. You may have multiple files of presets but the tool only uses the one named "presets.mat" when the TSM_Tool GUI is opened. You must change the name of the preset file you want to use *prior* to starting the TSM_Tool GUI. If "presets.mat" is not in the Matlab path one will be created in the current Matlab folder, containing a "Default" preset scenario and the nine examples in the "TSM: Theory and Practice" handbook.

The code uses several numerical algorithms and iterative processes to compute the results. If you become impatient with the time it is taking to complete a calculation, go to the command window in Matlab and type "Ctrl-C." This will terminate the code that is currently running and you will get an error message. If you want the code to run faster, increase the "Solver Time Step" and/or the "DTSM Time Step."

The model does not account for aircraft flying and handling qualities; things like angle-of-attack, sideslip, spiral stability, thrust, drag, and gyroscopic effects are not taken into account. Standard day conditions are assumed. The performance approximation method can be much better than assuming constant Mach, but it requires thoughtful use. If in doubt, start with the constant Mach approximation.

Sensitivity analysis is available. The user chooses variations from the critical dive recovery parameters displayed in the main TSM Tool window and the software calculates how much the TSM would change for each of those variations. Sensitivity analysis can be very valuable for determining where the most attention should be spent during diving maneuver planning and execution.

Figure C1 depicts the different parts of the GUI that will be referenced in this guide.

SETTING UP A CALCULATION

The value you enter for calculating TSM should be the worst-case expected values. For instance, if you are planning for a diving test point you should have a maximum allowable dive angle and minimum altitude to start recovery; these are the numbers that go into the "Initial Climb Angle" and "Initial Altitude." *Do not use the planned conditions, use the worst-case allowable test conditions.* If you aren't sure what the worst case is for your planned tolerances, this tool might be able to help; you can test different cases looking for the shortest TSM.

Units:

The TSM Awareness Tool may be used in metric or English units. When you change the selection, all of the relevant entries are automatically converted and the results (if calculated) are removed. If you go back-and-forth between the units the conversions may not be exact thanks to rounding.

Planned Dive Recovery Information:

Initial Climb Angle (-90 to 90 deg).

This is the climb angle of the aircraft before any delay. As with all vectors in this tool, it is in terms of the actual aircraft vector, not the body axis orientation. For instance, if the aircraft is expected to be in a -45-degree pitch attitude to achieve a 50-degree dive (-50-degree climb angle), enter "-50," not "-45."

Initial Bank Angle (0 to 180 deg).

The initial bank angle may only be entered in one direction but the resulting TSM data will be the same; there are no asymmetries that must be accounted-for in the algorithm (such as propellor torque and
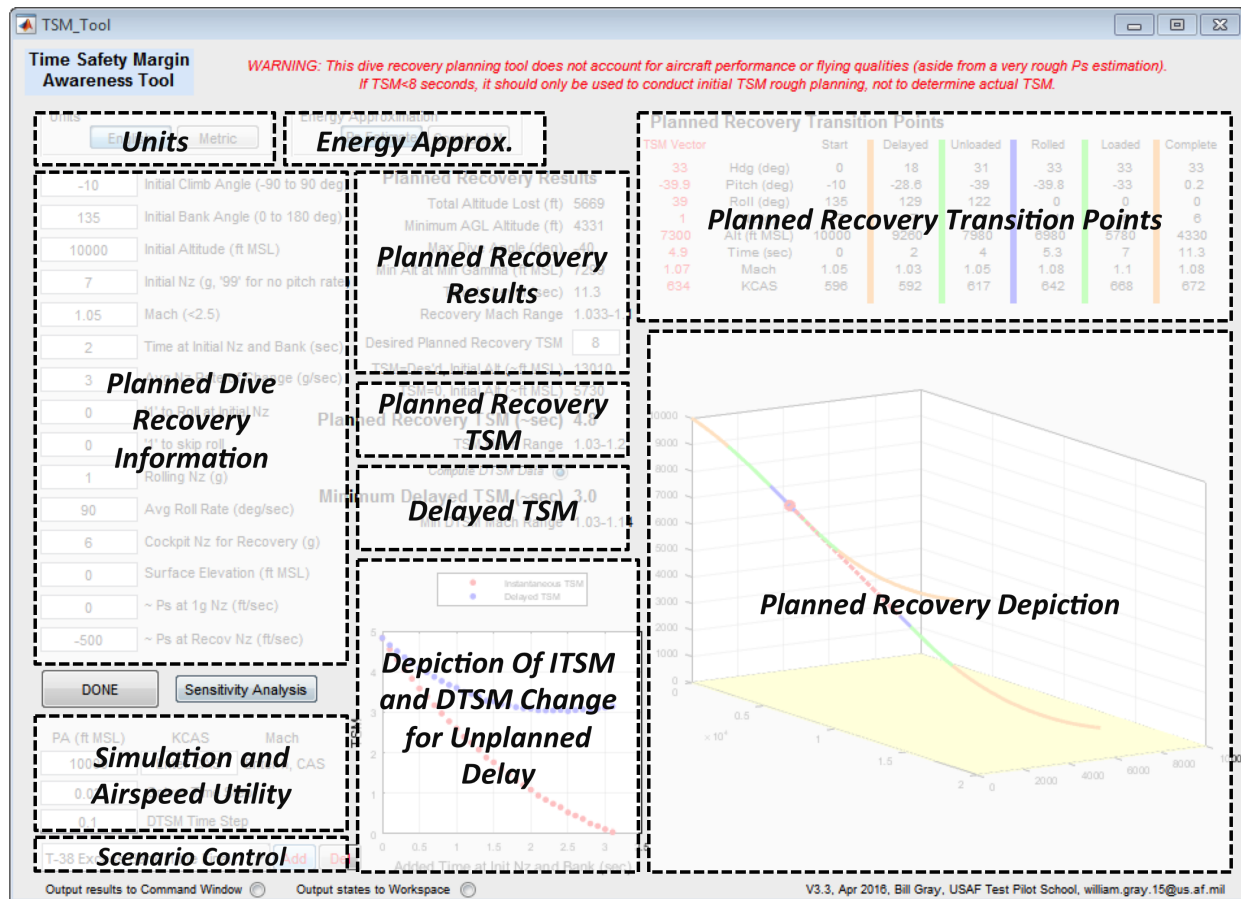
TSM_Tool

Time Safety Margin Awareness Tool

WARNING: This dive recovery planning tool does not account for aircraft performance or flying qualities (aside from a very rough Ps estimation). If TSM<8 seconds, it should only be used to conduct initial TSM rough planning, not to determine actual TSM.

Units

Energy Approx.

Planned Recovery Transition Points

	Start	Delayed	Unloaded	Rolled	Loaded	Complete
Hdg (deg)	0	18	31	33	33	33
Pitch (deg)	-10	-28.6	-39	-39.8	-33	0.2
Roll (deg)	135	129	122	0	0	0
Alt (ft MSL)	10000	9260	7980	6980	5780	4330
Time (sec)	0	2	4	5.3	7	11.3
Mach	1.05	1.03	1.05	1.08	1.1	1.08
KCAS	596	592	617	642	668	672

Planned Dive Recovery Information

Planned Recovery Results

Planned Recovery TSM

Delayed TSM

Depiction Of ITSM and DTSM Change for Unplanned Delay

Planned Recovery Depiction

Simulation and Airspeed Utility

Scenario Control

Output results to Command Window   Output states to Workspace   V3.3, Apr 2016, Bill Gray, USAF Test Pilot School, william.gray.15@us.af.mil

Figure C1 TSM Awareness Tool GUI Key

asymmetric configurations).

Initial Altitude (ft MSL) –or– (m MSL).

This is the initial altitude before any delay is added.

Initial Nz (g, '99' for no pitch rate).

The aircraft must be at some N_z prior to the start of the recovery. This might be an elevated N_z, as in the case of a wind-up turn or split-s, or it might be the N_z necessary to maintain a constant dive angle. If you enter "99" the tool will calculate the initial steady-state N_z required to produce a body-axis pitch rate of nil. If you set up a wings-level dive this N_z will be $g \cos(\gamma_0)$ where "g" is the acceleration due to gravity. If you have entered a non-zero bank angle for the initial condition and "99" for initial N_z, the initial N_z will be calculated as $g \cos(\gamma_0) \cos(\phi_0)$. Gravity still works, of course, so if you enter "0" for the initial N_z the dive angle will steepen during the delay time and until the recovery N_z increases enough to counter gravity.

Mach (<2.5).

This is the Mach number for the initial conditions. If you have selected "Constant M" in the energy approximation section of the tool, this Mach will be held throughout the recovery.

Time at Initial Nz and Bank (sec).

You may use this delay time—"initial delay"—however you see fit. For instance, you might add a few seconds of planned delay time to account for pilot reaction time to an unexpected "Recover!" call. It is also useful for maneuver construction, such as a planned pre-set time to maintain an initial condition. For instance, a test team might plan a maneuver that requires 10 seconds of time at an N_z of 0 g from a level flight starting condition.[2]

Avg Nz Rate of Change (g/sec).

To keep things simple, the same value for N_z rate of change is used for all N_z changes. It is best to underestimate this, as reduced N_z-onset rate will almost always decrease TSM.

'1' to skip unload to rolling Nz.

The algorithm assumes that the pilot will unload to the rolling N_z. If, for instance, you know that the N_z at the start of the recovery is less than the asymmetric N_z limit of the aircraft and the bank angle is less than 90 degrees, it might be prudent to skip unloading to roll.

'1' to skip roll.

Sometimes, the best recovery is accomplished by pulling through the nadir. Consider a split-s maneuver at a very high N_z that will be completed near the vertical. If the pilot unloads and rolls to the nearest horizon, the TSM can be much less than that achieved by just maintaining the initial N_z until recovery.

Rolling Nz.

This is the planned N_z for any bank angle changes that will be accomplished during the recovery. It might be safest to assume that the pilot will unload to 1 g for all rolls. (This is an ingrained habit for many fighter pilots.)

Avg Roll Rate (deg/sec average).

This roll rate is applied for the roll to wings level during the recovery. Note that it is an average roll rate, so if you plan on using the maximum available roll rate of the aircraft, you will need to enter a significantly reduced roll rate to account for roll acceleration and deceleration during the bank angle change.

Cockpit Nz for Recovery (g).

It is best to apply some conservatism here; do not plan on using the maximum available N_z unless you are willing to risk an overstress to improve your TSM. Choose a recovery N_z that will be available for the planned maneuver, taking into account limiters, stall speed, and so on.

Surface Elevation (ft MSL) –or– (m MSL).

The tool assumes level ground under the recovery; this is where you enter that elevation. Be sure to use a conservative estimate of the terrain elevation underneath the maneuver. If you plan to operate above rapidly-changing terrain, this tool cannot be reasonably used for TSM calculation unless you use the highest point that might be below the aircraft.

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[2] DTSM is calculated by adding additional delay to this step.

Energy Approximation:

The TSM Awareness Tool was originally designed to assume constant Mach for the entire maneuver. This method is still available by selecting "Constant M." Additional fidelity may be gained by selecting "Ps Estimate." This method uses a very simple mapping of P_s to determine the change in energy state as the maneuver progresses.

The specific excess power (P_s) connects the true altitude (h_T) and true airspeed (V_T) in accordance with the following equation.

$$P_s = \frac{dh_T}{dt} + \frac{V_T}{g}\frac{dV_T}{dt}$$

True airspeed changes to account for the total energy change if the vertical velocity is not equivalent to P_s. The TSM Awareness Tool takes advantage of this by using the estimated P_s provided by the user to predict the change in V_T during the recovery. The user provides this estimate in the form of two P_s values; the estimated P_s for the aircraft at 1 g and the estimated P_s for the aircraft at the specified recovery N_z.

The P_s used by the TSM Awareness Tool during calculations is based on a second-order curve fit between the 1 g and recovery N_z approximations, anchored by the assumption that the slope of the P_s curve is 0 at 0 g. When either value is changed in the tool, a graphical depiction of P_s as a function of N_z is shown on the GUI where the depiction of the ITSM and DTSM change for unplanned delay is normally displayed.

The resulting estimation is extremely limited. P_s is strongly influenced by N_z, power setting, altitude, and Mach number yet you can only provide two values based solely on N_z. If P_s charts are available, these values may be estimated based on an interpolation for the expected recovery conditions. If these expected conditions are not confirmed upon running the numbers through the TSM Awareness Tool, you should consider updating your estimates.[3] You may use the energy approximation to get a feel for the effect of energy changes on the dive recovery, but as the TSM decreases the simplifications employed in the TSM Awareness Tool will increase the likelihood that your actual TSM is significantly less than the tool predicts.

~ Ps at 1g Nz (ft/sec) –or– (m/sec).

Enter the estimated P_s for 1 g at the power setting you expect to use for the initial conditions and initial delay portion of the maneuver. The graphical depiction of P_s as a function of N_z depicted on the TSM Awareness Tool will update for the new information.

~ Ps at Recov Nz (ft/sec) –or– (m/sec).

Enter the estimated P_s for the recovery N_z at the power setting you expect to use for the recovery portion of the maneuver. The graphical depiction of P_s as a function of N_z depicted on the TSM Awareness Tool will update for the new information.

P_s vs N_z Depiction.

This only appears when the "P_s at 1g N_z" or "P_s at Recov N_z" is changed. If "Compute DTSM" is selected, when the TSM calculation is run the graph will be replaced by a depiction of the change of ITSM and DTSM as a function of unplanned delay time.

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[3] One value of P_s is relatively easy to calculate. If you are planning TSM for a constant airspeed dive, the P_s for the N_z of the dive will be equal to the vertical component of the true airspeed.

Simulation and Airspeed Utility:

CAS/Mach computation.

Mach number is of limited utility in most aircraft, but the TSM Awareness Tool is designed to "think" in Mach number.[4] You may enter the pressure altitude (PA) in feet MSL or meters MSL and/or the knots calibrated airspeed (KCAS)/CAS (kph) and the software will automatically update the values in the dive recovery information section. The resulting Mach number is retained if you change the initial altitude so you will have to re-enter the KCAS to compute the correct Mach number at the new altitude.

Solver Time Step.

The algorithm for the TSM Awareness Tool uses numerical methods to calculate the dive recovery data. It starts with the initial conditions then iterates over time until recovery is complete. The "Solver Time Step" defines the length of time for each iteration.

The default value of 0.02 seconds is more than accurate enough to keep the numerical method errors "within the noise" of the many other estimations that go into creating a profile. Increasing the time step will provide faster results but with some cost in accuracy. The tool limits this value to between 0.001 seconds (prioritizing accuracy over speed) and 0.1 seconds (prioritizing speed over accuracy). The former is more than accurate enough to be within the errors produced by the methodology, and the latter will begin to show significant inaccuracies caused by stepping through the numeric calculation too quickly.

DTSM Time Step.

Estimating DTSM requires determining how ITSM changes as unplanned delay is added. The DTSM time step is the step size that the software uses as it increments the unplanned delay time to find the how the DTSM changes with increasing unplanned delay. Increasing this value makes the tool run faster but might reduce the quality of the DTSM estimate. The tool limits this value to no less than twice the solver time step.

RUNNING THE CALCULATION

The prominent "RUN" button is used to start the calculation process. The button will read "Standby" while the calculation is underway and "DONE" once it is complete. If any of the inputs are changed, the results are cleared and the button returns to displaying "RUN."

PRESENTATION OF RESULTS

Planned Recovery Results:

These data are strictly based on the planned dive recovery information, including time at initial N_z and bank. If the aircraft is in a climb at the end of the planned delay, the planned recovery TSM and DTSM are not calculated because the aircraft was not in a dive at the beginning of the recovery.

Total Altitude Lost (ft) –or– (m).

The difference in altitude between the initial altitude and the dive recovery altitude. Any climbing that occurs during the initial delay is accounted for.

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[4] Why would this be? Because of history; the original purpose of the algorithm was to look at dive recoveries for fighter aircraft at high speed, where Mach is predominantly used as a pilot reference for speed.

Minimum AGL Altitude (ft) –or– (m).

The minimum AGL during the recovery. This will always occur at the moment the aircraft achieves level flight, provided that it does not recover during the initial delay.

Max Dive Angle (deg).

All dive recoveries have a maximum dive angle (minimum γ). Sometimes this will occur at an unexpected point during the recovery. This value corresponds to the maximum dive angle achieved during the entire maneuver, including the user-specified initial delay time.

Min Alt at Min Gamma (ft MSL) –or– (m MSL).

The minimum altitude at the maximum dive angle is a critical component in calculating ITSM. It defines the ITSM vector.

Time to Level (sec).

Most dive recoveries are very short-duration events.[5] The "time to level" is the amount of time between the initial conditions and achievement of level flight during the recovery. The aircraft may be in a climb during the initial delay time—such as when a split-s maneuver is started during a climb—but the algorithm does not check for a climb until the initial delay time is over. If the aircraft is in a climb at the end of the initial delay time, no dive recovery is necessary so the recovery is complete before it started.

Recovery Mach Range.

This result is visible when "Ps Estimate" is selected for the energy approximation and hidden when "Constant M" is selected. It shows the Mach range encountered during the entire recovery maneuver.

Planned Recovery Transition Points and Planned Recovery Depiction:

The TSM Awareness Tool constructs all recovery maneuvers from the same set of steps; start, initial delay, adjust to rolling N_z, roll, load to recovery N_z, pull until recovery. This section of the GUI shows the state of the aircraft at each transition. To help interpret the graphical depiction of the recovery path, the color of the path between each mode point is the same color as the bar separating the mode points.

The planned recovery depiction also shows the predicted path for the TSM-defining recovery, with a dashed red line depicting the TSM path; this line will always start at the worst-case point in the planned recovery. The ground is depicted as a sand-colored surface.

If you move your mouse cursor over the planned recovery depiction, the mouse cursor will turn into a little circular arrow and you can click and hold on the graph to rotate it and look at the recovery from different angles.

TSM Vector.

The point during the recovery that is used for computing TSM (the steepest dive angle at the lowest altitude) is depicted in red on the left side of the planned recovery transition points chart. It is also depicted

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[5] This property makes an algorithm like the one used in this tool possible. Thank to the limitations of numerical methods, as the length of the recovery increases, the accuracy of the TSM Awareness Tool decreases.

on the planned recovery depiction as a large red dot. Depending upon the geometry of the recovery, this point may appear anywhere from the initial conditions to the point during the final wings-level pull when the N_z increase begins to reduce the dive angle.

Planned Recovery TSM:

The data in this section is based on the worst-case planned maneuver, including planned initial delay entered as "Time at Initial Nz and Bank."

Desired Planned Recovery TSM.

It is common to seek a minimum TSM for a test point. The TSM Awareness Tool will calculate the initial altitude that produces the desired TSM and show the results as "TSM=Des'd, Initial Alt (~ ft MSL)." The default value for the desired planned recovery TSM is 8 seconds.

TSM=Des'd, Initial Alt (~ ft MSL).

This is the initial altitude necessary to provide the "desired TSM." The result is based on the Mach calculated for the specified initial altitude so if the entry airspeed is not defined as a Mach number you will need to re-run the model from the estimated initial altitude with the correct Mach number for that altitude.

TSM=0, Initial Alt (~ ft MSL).

This is the initial altitude that will provide no time safety margin.

Planned Recovery TSM (~ sec).

This is the TSM for the planned recovery, including planned delay entered as "Time at Initial Nz and Bank."

TSM Mach Range.

This result is visible when "Ps Estimate" is selected for the energy approximation and hidden when "Constant M" is selected. It shows the Mach range encountered during the entire TSM-defining recovery maneuver including the time on the TSM vector. The maximum Mach can be surprisingly high when TSM is long and the P_s is not very low because the TSM vector calculates the acceleration of the aircraft using the P_s estimate; this estimate does not take into account such things as aircraft limits, terminal velocity, wave drag, etc. In most transonic cases, the actual TSM will be significantly longer because the Mach will be limited to less than that estimated by the rough energy approximation.

Delayed TSM:

Compute DTSM Data.

Select this to have the TSM Awareness Tool calculate the DTSM. Calculating DTSM usually requires much more time than calculating the TSM for the planned maneuver. Deselect this option if calculating DTSM is unnecessary or premature.

Minimum Delayed TSM (~ sec).

The TSM Awareness Tool adds increments of unplanned delay to the "Time at Initial Nz and Bank" until the aircraft contacts the surface elevation during recovery or the recovery occurs during the unplanned

delay. For instance, a split-s maneuver started high enough and continued at the entry N_z will eventually result in a climb and obviate the need for a recovery. The algorithm incrementally adds additional unplanned delay to the time at initial N_z and bank then calculates a new ITSM with that unplanned delay. The DTSM for that additional unplanned delay is equal to the unplanned delay plus the associated ITSM. This process continues until the ITSM for the unplanned delay increment either becomes less than zero or the aircraft completes the recovery during the unplanned delay. The result shown here is the minimum DTSM for the range of unplanned delays.

Keep in mind that the flight parameters that go into the flight path for the unplanned delay are simply a continuation of the planned recovery parameters. If you expect significant N_z or bank angle overshoot that would increase the rate at which the dive angle is steepening, use the maximum expected N_z and bank angle to ensure sufficient conservatism in your DTSM values.

Min DTSM Mach Range.

This result is visible when "Ps Estimate" is selected for the energy approximation and hidden when "Constant M" is selected. It shows the Mach range encountered during the entire TSM-defining recovery maneuver for the amount of unplanned delay that produces the minimum DTSM.

Depiction of ITSM and DTSM Change for Unplanned Delay:

The change of ITSM and DTSM (recall that DTSM is the sum of the unplanned delay and the ITSM resulting from that unplanned delay) is depicted in a graph. In a constant Mach, constant dive angle setup the DTSM remains constant because each added second of unplanned delay reduces the ITSM by a second. More complex recoveries will cause the DTSM to change with time. Discontinuities might be present as unplanned delay causes the recovery algorithm to take a different path. For instance, a short split-s maneuver will result in an unload-roll-load recovery but as additional unplanned delay is added the unload-roll-load sequence will become unnecessary because the unplanned delay time will cause the aircraft to pull through the nadir, eliminating the need to roll to the nearest horizon.

SELECTING, ADDING, AND DELETING SCENARIOS

A drop-down menu is available to choose scenarios. Scenarios may be added by selecting the "Add" button, entering a preset scenario title, and selecting "OK." To delete a scenario, select it from the drop-down list, select "Del," and select "OK." Only the scenario setup is stored. You must run the simulation to get the results.

Presets are stored in the same folder as the GUI and code, in a file called "presets.mat." If you want to have separate preset files you can duplicate the existing preset file, change the name of the old file to something other than "presets.mat," and name the new file "presets.mat." The TSM Awareness Tool only uses the file named "presets.mat" and will terminate execution for an error while opening the GUI if the file is in the wrong format. There is no "undo" command available when you delete a scenario.

SENDING RESULTS TO THE MATLAB WORKSPACE

Advanced users might want to run multiple scenarios so they can use the data to analyze changes in the recovery strategy. For instance, you could run a series of scenarios with different values of recovery N_z so you can chart the dependency of TSM on recovery N_z. If you select "Output results to Command Window" the results of the simulation will be placed in the Command Window in the order shown in table C1. For

more detailed analysis, you may use "Output States to Workspace." At the completion of the run, the state vectors for the planned recovery ("state1"), the worst case vector ("mingamma_state"), and the recovery with the TSM path ("state2") will be placed in the Matlab Workspace. The definition and units of the state vector are in the cell array "state_units."

Table C1 Results Placed in the Matlab Workspace

1	Units	12	Rolling Nz	23	Max Dive Angle
2	Energy Approximation	13	Roll Rate	24	Min Alt at Max -gamma
3	Initial Climb Angle	14	Cockpit Nz for Recovery	25	Min Mach During Recovery
4	Initial Bank Angle	15	Surface Elevation	26	Max Mach During Recovery
5	Initial Altitude	16	Ps at 1g Nz	27	Time to Level
6	Initial Nz	17	Ps at Recov Nz	28	Planned Recovery (PR) TSM
7	Mach	18	Solver Time Step	29	Minimum DTSM
8	Time at Initial Nz and Bank	19	DTSM Time Step	30	0 PR TSM Init Alt
9	Nz Rate of Change	20	Compute DTSM	31	Des'd PR TSM
10	Skip unload to rolling Nz	21	Total Altitude Lost	32	Des'd PR TSM Init Alt
11	Skip roll	22	Minimum AGL Altitude		

TSM SENSITIVITY TO CHANGES

It can be very helpful to know how additional errors might affect the anticipated TSM. For instance, a small increase in dive angle might have much greater consequence than a small decrease in recovery N_z. Sensitivity analysis is accessed by selecting the eponymous button next to the "Run" button on the TSM Tool.

Variation:

The analysis will be conducted based on the amount of variation provided by the user in the "Variation" column of entry boxes (See figure C2). These variations are applied to the parameters in the TSM tool one at a time to calculate the change in TSM for each variation. When the sensitivity analysis (SA) window is opened, default variations are automatically entered but you may change them to meet your needs. The value that the TSM Tool will use to calculate TSM is shown in the next column. Select "Run" to find the results.

Figure C3 depicts the SA window after a run with the "Default" TSM Tool parameters and the default SA parameters. The results are depicted in two ways, in the "TSM secs per Variation" column and graphically in the small windows under the "Points" menu.

TSM secs per Variation:

The values in this column show the change in the TSM for the variation provided by the user. For instance in figure C3, -5 degrees of variation in the initial climb angle (corresponding to a 50-degree dive) results in a TSM reduction of 0.78 seconds. A reduction in the recovery N_z of -0.5 g (corresponding to a 5.5-g recovery) only decreases the TSM by 0.20 seconds. In this example, it might be prudent to pay more attention to the dive angle than to the recovery N_z.
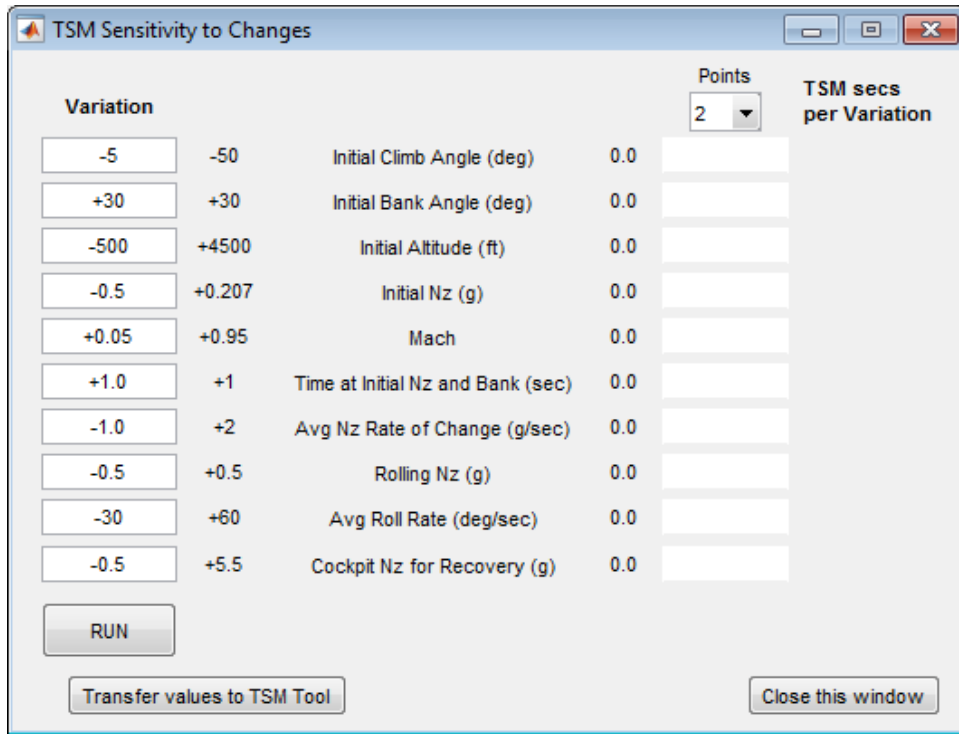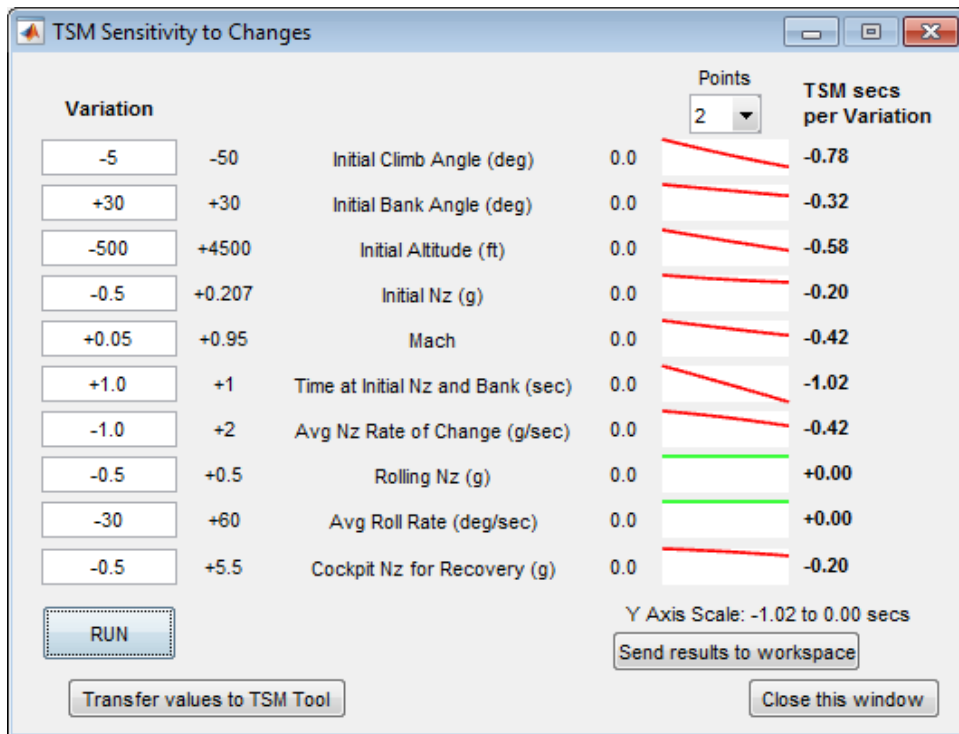
Figure C2 Sensitivity analysis window

Figure C3 Sensitivity analysis window

Points:

The small graphs under the "Points" pull-down depict how the TSM is changing on its way to the specified variation. All of the graphs have the same Y axis scale so you can see the relative effect of the variations by comparing the slope of their curves. (The Y axis is the delta-TSM axis; the scale is given at the bottom of the column of graphs. The X axis is the variation, from zero on the left to the selected variation on the right.) If the TSM is increasing or unchanged for the variation, the curve is green.

You choose the number of points (in addition to the first point for zero variation and zero TSM change) to be calculated for these graphs. By choosing two or more, you can better see how the TSM is changing as it approaches the chosen variation. The importance of knowing how TSM is changing can be seen in figure C3 by examining the graphs for the initial climb angle and cockpit N_z for recovery. In the former, the rate of TSM change is decreasing with the variation; the TSM is getting worse but the rate of that change indicates that doubling the variation will not double the reduction in TSM. In the latter, the slope is increasing; doubling the variation for the recovery N_z will likely more than double the reduction in TSM. Two points are usually enough to see these trends over small variations; up to eight are available if you are willing to wait. If you choose one point, the graphs will be straight lines.[6]

Transfer values to TSM Tool:

If you want to find out the cumulative effect of all of the variations, you can transfer them to the TSM Tool. When you do this, the values that were in the Tool are stored. You can put them back using a button labeled "Restore TSM Tool values." This button will appear when you first transfer the adjusted values to the TSM tool.

Send results to workspace:

You can send the results of the sensitivity analysis run to the Matlab workspace by selecting "Send results to workspace" after the run is complete. This button is hidden until there are results to send. The results are given in a Matlab cell array with row and column headings.

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[6] The graphs are second-order curve fits of the results. The actual results are plotted as a gray line that is thinner than the fitted line. If the curve fit is poor, you will see the gray line and can make your own assessment of the results.

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APPENDIX D – ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Acronym	Definition	Units
AFB	Air Force Base	-
AFFTC	Air Force Flight Test Center	-
AFFTCI	Air Force Flight Test Center Instruction	-
AFI	Air Force Instruction	-
AFMC	Air Force Material Command	-
AFTC	Air Force Test Center	-
AFTCI	Air Force Test Center Instruction	-
AGL	Above Ground Level	-
AOA	Angle of Attack	-
ART	Available Reaction Time	-
CAS	Calibrated Air Speed	-
CFIT	Controlled Flight Into Terrain	-
CTF	Combined Test Force	-
DTSM	Delayed Time Safety Margin	-
EAS	Equivalent Air Speed	-
FLCS	Flight Control System	-
FPA	Flight Path Angle	-
GCAS	Ground Collision Avoidance System	-
GLOC	g-Induced Loss of Consciousness	-
GUI	Graphical User Interface	-
IAW	In Accordance With	-
ITSM	Instantaneous Time Safety Margin	-
KCAS	Knots Calibrated Airspeed	-
KTAS	Knots True Airspeed	-
M&S	Modeling and Simulaton	-
MN	Mach Number	-
MSA	Minimum Safe Altitude	-
MSL	Mean Sea Level	-
NASA	National Aeronautics and Space Administration	-
PA	Pressure Altitude	-
PR	Planned Recovery	-
RPM	Revolutions Per Minute	-
SRB	Safety Review Board	-
TPS	Test Pilot School	-
TSM	Time Safety Margin	-
TTI	Time to Impact	-
TTU	Time to Unrecoverable	-
USAF	United States Air Force	-

Abbreviation	Definition	Units
deg	degree or degrees	-
ft	foot or feet	-
kph	kilometer or kilometers per hour	-
lb	pound or pounds	-
sec	second or seconds	-

Symbol	Description	Units
C_L	Coefficient of lift	-
g	Local gravitational acceleration	ft/sec^2
h_0	Height (MSL) at the start of the recovery phase	ft
h_S	Surface elevation (MSL)	ft
h_T	True altitude (MSL)	ft
M_0	Mach number at the start of the recovery phase	-
N_z	Normal acceleration	g
N_{z0}	Normal acceleration at the start of the recovery phase	g
N_{zr}	Normal acceleration for the wings-level recovery pull-out	g
$N_{z\dot{\phi}}$	Normal acceleration for rolling	g
$\dot{N}_z$	Rate-of-change of normal acceleration	g/sec
P_s	Specific excess power	ft/sec
S	Wing surface area	ft^2
t_d	Planned delay at the beginning of the recovery phase	sec
$\bar{q}$	Dynamic pressure	lb/ft^2
V_T	True airspeed	ft/sec
γ	Climb angle	deg
γ_0	Climb angle at the start of the recovery phase	deg
ϕ	Bank angle	deg
ϕ_0	Bank angle at the start of the recovery phase	deg
$\dot{\phi}$	Roll rate	deg/sec

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